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Optimizing raised bed dimensions for enhanced maize yield, water footprint reduction, and improved soil moisture dynamics under furrow irrigation

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Abstract. *Islam MT, Bhuyan MY, Das N, Jahan N, Rahman MM, Jewel MAH, Adham AKM. 2024. Optimizing raised bed dimensions for enhanced maize yield, water footprint reduction, and improved soil moisture dynamics under furrow irrigation. Asian J Agric 8: 10-22.* Effective water management is crucial for sustainable agriculture, especially in regions facing water scarcity. This study examines the impact of different Raised Bed (RB) dimensions on maize (*Zea mays* L.) yield, Water Footprint (WF), and soil water content under furrow irrigation, with a focus on water conservation. The experiment, conducted at Bangladesh Agricultural University, Bangladesh, utilized a randomized complete block design featuring four irrigation treatments: the Conventional Method (CM) and three RB configurations with widths of 25 cm, 65 cm, and 110 cm. The RB65 treatment significantly improved maize yield, achieving 13.1±1.4 t/ha compared to 9.89±1.11 t/ha with CM. Additionally, RB65 peaked in water productivity, reducing irrigation water use by 37.72%, highlighting its potential for water conservation. Soil moisture retention was consistently higher across all RB treatments, with RB65 showing the greatest retention at depths up to 80 cm. It also recorded the lowest green WF (88.6±10.07 l/kg) and blue WF (12.63±1.43 l/kg), resulting in the lowest total WF (101.22±11.50 l/kg). These findings suggest that RB systems, particularly the 65 cm configuration, optimize water usage and enhance maize productivity, making it a viable strategy for resource management in water-limited areas. The study recommends adopting the RB65 configuration to maximize water efficiency and crop yields, contributing to food security and sustainable agricultural practices. However, these results are based on specific geographical and climatic conditions, limiting their generalizability to other regions or crops. Future research should explore long-term studies across diverse agro-ecological zones and examine various crops to validate the broader utility of the RB65 configuration.

Keywords: Maize yield, raised bed irrigation, soil water content, sustainable agriculture, water footprint, water management

INTRODUCTION

Water is undeniably crucial for the agricultural industry, serving as the foundation of food production. Agriculture, as the largest user of global water resources, accounts for approximately 70% of freshwater withdrawals, primarily for irrigation (Jeong and Zhang 2020). This heavy reliance places agriculture at the heart of global water scarcity challenges. While essential for food production, conventional agricultural practices, particularly inefficient irrigation methods, contribute significantly to water depletion, exacerbating the very scarcity upon which agriculture depends (Roushan et al. 2023). Among surface irrigation technologies, furrow irrigation is the most prevalent due to its simplicity and cost-effectiveness. It is widely used in water-stressed regions, such as arid and semi-arid areas, where water management is critical (Akbar et al. 2016; Mekonnen et al. 2020). Studies in Egypt and South Asia demonstrate that furrow irrigation can reduce water use while maintaining or improving crop yields for staple crops like maize and wheat (Sarker et al. 2020; Ismail et al. 2021; Yigezu et al. 2021). However, despite its popularity, furrow irrigation is associated with inefficiencies such as deep percolation and runoff, leading to significant water loss (Setu et al. 2023). Thus, optimizing these systems is vital for sustainable water management.

The adoption of improved water-saving agricultural practices, such as enhanced furrow irrigation and Raised Bed (RB) systems, can have profound socioeconomic impacts. These methods not only conserve water but also increase crop yields, thereby promoting food security and offering economic benefits to smallholder farmers, especially in developing countries like Bangladesh, where water scarcity limits agricultural potential (Sarker et al. 2020). Additionally, water-efficient practices reduce production costs, increase labor efficiency, and enhance resilience to climate variability, ultimately improving the livelihoods of rural communities (Yigezu et al. 2021). By boosting irrigation efficiency, these technologies significantly enhance water productivity and enable better resource management across agricultural systems (Islam et al. 2022; Rahman et al. 2022). Notably, 97.8% of farmers' fields are irrigated using surface methods, underscoring the widespread dependence on traditional systems, despite their water loss issues (Setu et al. 2023). Therefore, more efficient practices like improved furrow irrigation are critical to addressing these inefficiencies and supporting sustainable agriculture.

Maize (*Zea mays* L.), one of the most widely cultivated crops, is crucial for global food security (Das et al. 2018; Tizhe et al. 2023; Diri and Kedoneojo 2024). However, climate-related shocks have caused a 3.8% decline in maize yields in recent decades, with projections of a 24% decrease by the end of the 21st century (Markos et al. 2023). This is because of poor soil nutrients, water scarcity, and soil nitrogen deficiency (Islam et al. 2017). In developing countries like Bangladesh, water scarcity hinders agricultural potential (Makate et al. 2019). Traditional flooding irrigation is inefficient, leading to significant water loss and reducing aeration and nitrogen absorption (Majeed et al. 2015; Rahman et al. 2022).

Water Footprints (WFs) are a crucial indicator for expressing water resources needed for goods and services, categorized into green, blue, and grey WFs (Khan and Ali 2024). Use of WF in managing limited water resources among competing sectors is emerging as a highly promising approach. In particular, agricultural water management stands to benefit significantly from this method, as WF variability is strongly influenced by factors such as climate, soil types, and water management strategies (Feng et al. 2021). Recent studies focus on the WF of specific crops, including maize, across global, national, and regional scales (Chapagain and Hoekstra 2011; Elbeltagi et al. 2020; Li et al. 2020; Al-Gaadi et al. 2022). These studies highlight the importance of understanding the spatiotemporal variability of WFs and their implications for crop production.

Maize requires sufficient water, especially during early growth, flowering, and seed-filling stages, as water scarcity at these stages can severely impact production (Muslimah et al. 2023). Waterlogging during flowering can reduce grain output by about half (Kaur and Kaur 2022). Thus, improving water management is vital to boost maize yields (Muslimah et al. 2023). Planting on RBs is an effective water-saving technique that mitigates the impact of flooding during irrigation and heavy rainfall (AbdelRahman and Arafat 2020). RB planting enhances water absorption efficiency and evenly distributes irrigated water, reducing water usage by up to 50% and increasing yields by 20-25% compared to traditional irrigation systems (Verhulst et al. 2011; Rashwan et al. 2024). However, the effectiveness of RBs depends on factors like bed size, implementation method, sowing technique, and seed rates (Akbar et al. 2016; Yigezu et al. 2021). Improper sizing of RB installation can lower yields (Yigezu et al. 2021).

Furrow-irrigated RB cultivation systems are crucial for sustainable agriculture, providing efficient water use and increased yields (Shah et al. 2024). The bed size (i.e., width) of an RB can have significant effects on soil wetness, thereby, influencing crop growth and yield (Pan et al. 2019; Duan et al. 2021). While the benefits of RB systems under varied agricultural conditions are well-documented, the specific effects of different RB dimensions on maize cultivation remain poorly understood. Although existing research highlights the water-saving benefits of RB farming, there is a significant lack of studies on how varying RB widths affect crop yield and WFs.

This study aims to investigate effects of different furrow-bed configurations on enhance maize yield, water productivity, and soil water content. It also seeks to provide a comprehensive understanding of the WFs associated with maize cultivation, crucial for developing sustainable agricultural practices and improving resource management in regions with limited water availability. The research will contribute valuable insights to optimize irrigation practices, ultimately supporting food security and sustainable water use in agriculture.

MATERIALS AND METHODS

Experimental site with soil and climatic conditions

The experiment was conducted at the Bangladesh Agricultural University (BAU) farm in the Mymensingh District, Bangladesh, following the procedures outlined in Figure 1. The study site is situated in agro-ecological zone 9, at coordinates 24.75° N latitude and 90.50° E longitude, with an elevation of 18 meters above mean sea level (Figure 2). A comprehensive analysis of the soil's physical, chemical, and biological properties was conducted by the Agri-Varsity Humboldt Soil Testing Laboratory. According to the Bangladesh Agricultural Research Council (BARC 2005), the soil texture class of the experimental field is silt loam, underlain by sandy loam, characteristic of the Old Brahmaputra Floodplain. Key soil characteristics measured include bulk density (1.31 g/cm³), field capacity (31.33%), electrical conductivity (250-345 µS/cm), and wilting point (16.05%).

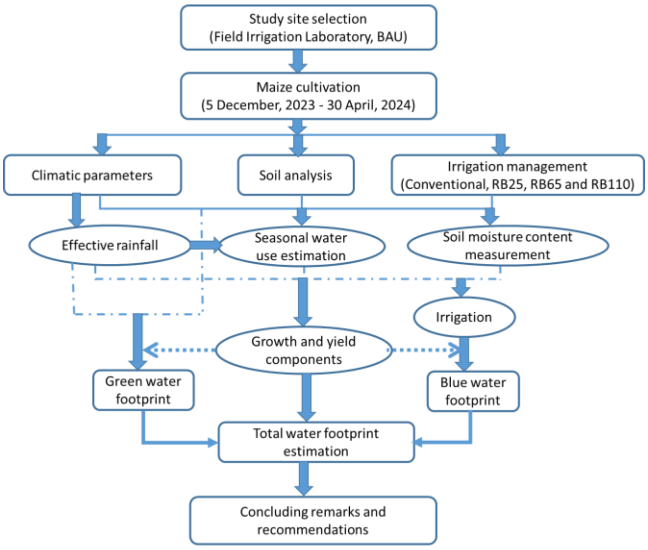

Figure 1. Flow diagram outlining the methodologies used in this study. RB denotes the raised bed-based furrow irrigation technique, implemented with varying bed widths of 25 cm, 65 cm, and 110 cm

Table 1. Weather data for the experimental site throughout the maize growing period (from 5 December, 2023 to 30 April, 2024)

Parameters	**Months**				
	December	**January**	**February**	**March**	**April**
Rainfall (mm)	26.5	0	17.3	72	0.2
Mean maximum air temperature (°C)	24.1	20.1	23.7	27.2	33.5
Mean minimum air temperature (°C)	18	13.8	17.7	21.1	26.1
Monthly average relative humidity (%)	84.2	86.5	76.4	76.3	76.5
Mean evaporation (mm)	2.15	1.6	2.63	3.5	4.79
Mean wind speed (km/h)	0.37	1.71	2.6	4.6	7.63
Mean sun shine (hours)	5.56	3	5.93	6.93	7.19

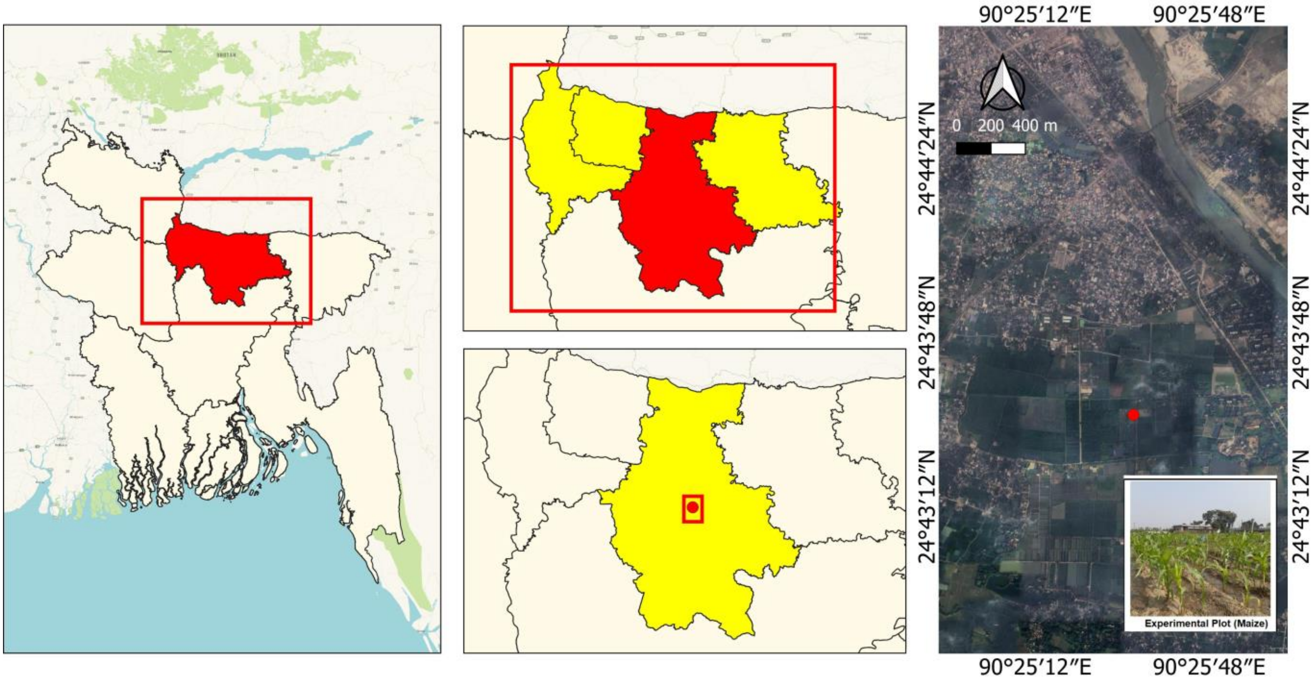

Figure 2. Geographical location of the experimental site at the Field Irrigation Laboratory of Bangladesh Agricultural University, Mymensingh, on the map of Bangladesh

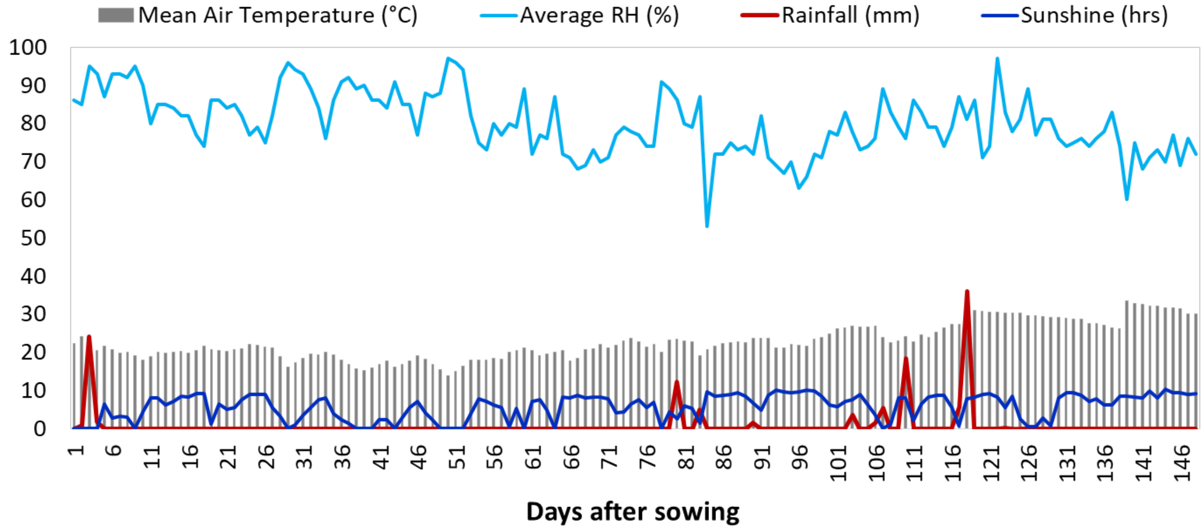

Figure 3. Weather data recorded at the experimental site during the days following maize sowing

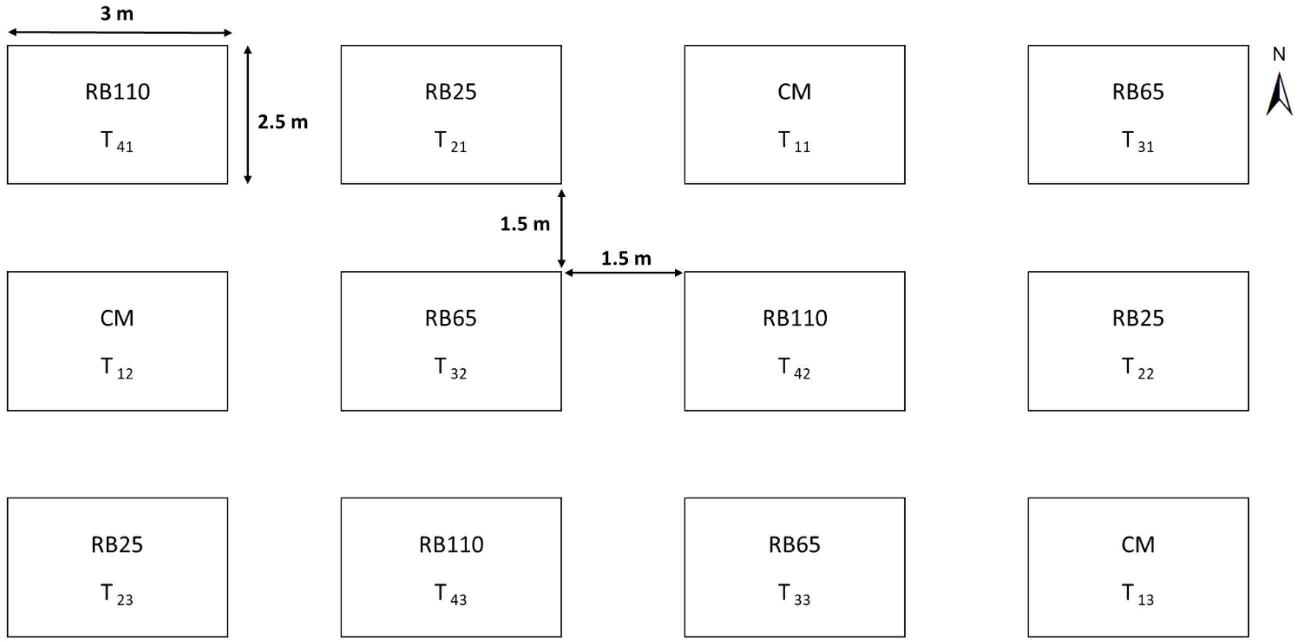

Figure 4. Layout of the field experiment, illustrating the different irrigation treatments: CM represents the Conventional Method, while RB110, RB65, and RB25 denote Raised Bed (RB)-based irrigation methods with bed widths of 110 cm, 65 cm, and 25 cm, respectively

Climatic variables, including temperature, sunshine hours, wind speed, relative humidity, rainfall, and evaporation, were gathered from the Bangladesh Agricultural University (BAU) weather station, operated by the Bangladesh Meteorological Department (Table 1). Additionally, a plot was created to visualize meteorological data, such as sunshine, rainfall, relative humidity, and mean air temperature, illustrating the weather conditions during the maize growing season (Figure 3).

Experimental setup and irrigation treatments

A randomized complete block design was employed for the experimental layout, comprising 12 plots, each measuring 3 meters by 2.5 meters. Four different irrigation treatments were tested, with each treatment replicated three times. The treatments included a Conventional Method (CM) as a control and three irrigation strategies tailored to different bed widths (25 cm, 65 cm, and 110 cm). In all treatments, plant spacing within each plot was standardized to approximately 20 cm between plants to ensure uniformity. Each plot consisted of six rows, with 13 plants per row, spread across a 3-meter-wide area with 25-cm furrows. The row-to-row distance was consistently maintained at 50 cm across all treatments. For the RB-based irrigation conservation method with a 25-cm bed size (RB25), planting was conducted over six beds, with one row per bed. For the 65-cm bed size (RB65), planting was arranged over three beds, with two rows per bed, while for the 110-cm bed size (RB110), planting took place over two beds, with three rows per bed. Figure 4 illustrates the field configuration used for this experiment. The specific treatments with various irrigation techniques and bed sizes are as follows:

T_{11}, T_{12} and T_{13} = Conventional Method (CM), i.e., flooding irrigation

T_{21}, T_{22} and T_{23} = RB-based conserving irrigation with 25 cm bed size (RB25)

T_{31}, T_{32} and T_{33} = RB-based conserving irrigation with 65 cm bed size (RB65) and

T_{41}, T_{42} and T_{43} = RB-based conserving irrigation with 110 cm bed size (RB110)

Field works and data recording

The field was meticulously prepared before the experiment, involving plowing, harrowing, and planking to ensure optimal soil conditions. It was cleared of weeds and crop residues. Fertilizer application followed standard guidelines (AIS 2019) for hybrid maize production in Bangladesh, using 550 kg/ha of urea, 250 kg/ha of triple super phosphate, 200 kg/ha of muriate of potash, and 250 kg/ha of gypsum. Maize seeds (*Taj* variety) were sown at a rate of 25 kg/ha. Uniform intercultural practices were applied to all plots, except for irrigation treatments. Irrigation management was based on soil moisture content and key growth stages. Moisture levels were monitored using a soil moisture profiler (Delta-T Device Co., UK), and irrigation water was applied into furrows in RB plots until water level reached the bed level. Rainfall data were collected from the nearby BAU weather station. Weed control was conducted twice, and the crop was harvested at full maturity.

Determination of leaf area and harvest indices of maize

Plant growth dynamics are widely expressed by Leaf Area Index (LAI), which measures the one-sided leaf area per unit ground area of a crop field. During the growing season, leaf area measurements were taken three times: the first measurement was taken 34 Days After Sowing (DAS), followed by subsequent measurements at 40 and 69 DAS, respectively. A LI-3100 Leaf Area Meter was used to measure leaf area of collected samples. The LAI was computed using the following equation (Islam et al. 2022; Munmun et al. 2024).

$$\text{LAI} = \frac{\text{Leaf area of the sample } (m^2)}{\text{Area of land covered by the sample } (m^2)}$$

Crop maturity was determined by observing the browning of the plant's husks and leaves. To establish initial plant density, the number of plants within a square meter of each plot was counted. Plant height was measured from the ground to the highest spike, and the number of ears per plant was recorded. At maturity, a 1 m x 1 m area in the central section of each plot was designated for harvesting, with the rest of the plot also harvested separately. The yield from the marked area was collected, labeled, and sun-dried to gather grain. Yield was estimated at ~12% of grain moisture content. For calculating harvest indices, the perimeter and length of each ear were measured, and the number of rows and grains per ear was counted. Ears were picked, dried, and shelled plot by plot. A sample of one thousand clean, dried grains was weighed to calculate yield, which was extrapolated to estimate the total plot yield in kilograms per hectare (kg/ha). Straw yield was determined by drying and weighing straw from the 1 m^2 area, with results also converted to kg/ha. The biological yield, recorded for each plot in kg/ha, was the sum of the grain and straw yields. The harvest index (HI) was calculated using the following formula (Hossain et al. 2019; Islam et al. 2022; Munmun et al. 2024):

$$\text{Harvest index } (\%) = \frac{\text{Grain yield}}{\text{Biological yield}} \times 100$$

Estimation of water productivity and water footprints

The total crop-water use during the growing season was calculated by summing the irrigation water applied and the rainfall received. The seasonal Effective Rainfall (ER) was calculated according to the methodologies detailed by Islam et al. (2015). Crop-water use was mathematically represented as described by Michael (1978):

$$WU = IR + ER$$

Where:
WU: Seasonal crop-water use (cm)
IR: Total irrigation water applied (cm)
ER: Seasonal effective rainfall (cm)

Crop-water productivity, also known as Field Water Use Efficiency (FWUE), is calculated using the ratio of crop yield to the total amount of water utilized during the crop's growing cycle (Hossain et al. 2019; Islam et al. 2022; Munmun et al. 2024).

$$\text{FWUE} = \frac{Y}{WU}$$

Where:
FWUE: Field-water use efficiency or crop-water-productivity (kg/ha/cm)
WU: Seasonal crop-water use in the crop field (cm)
Y: Grain yield (kg/ha)

The concept of WF, as proposed by Hoekstra and Hung (2003), is an indicator of water appropriation, indicating the volume of water used by a crop (Rodriguez et al. 2015). When discussing WF for crop production, the terms GWF and BWF refer to the consumption of precipitation and irrigation water, respectively (Islam et al. 2024). These metrics enable the assessment of their respective contributions to the Total Water Footprint (TWF), which is the sum of GWF and BWF, expressed in liters per kilogram of maize.

$$\text{GWF} = \frac{\text{GWU}}{\text{Yield}}$$

$$\text{BWF} = \frac{\text{BWU}}{\text{Yield}}$$

$$\text{TWF} = \text{GWF} + \text{BWF}$$

Measurement of soil moisture content

Soil moisture content readings were obtained from the selected experimental plots three times a day. Due to restricted access to some plots, measurements were taken from 4 of the 12 plots, with one plot representing each technique under investigation. A HH2 moisture meter (Delta-T Device Co., UK) was used to record soil moisture content at predetermined depths of 10 cm, 20 cm, 30 cm, 40 cm, and 80 cm.

Statistical analyses

Using the methodology of Gomez and Gomez (1984), an Analysis of Variance (ANOVA) was conducted to evaluate the effects of various treatments on the growth, yield-contributing variables, and FWUE of irrigated maize. The standard error method was employed to assess the significance of differences between treatment means.

RESULTS AND DISCUSSION

Growth and yield-contributing attributes of irrigated maize

The study analyzed various growth and yield-contributing attributes of irrigated maize under different RB dimensions and the CM. Key metrics such as plant height, ear length, ear perimeter, productive kernel number per ear, kernel weight per ear, and 1000-kernel weight were measured (Table 2). The CM treatment resulted in the tallest plants with an average height of 224.167±38.81 cm, while the shortest plants were observed in the RB110 treatment, averaging 212.81±31.80 cm. Ear length and ear perimeter are critical indicators of maize yield potential. The RB65 treatment outperformed others, achieving the highest ear length (17.385±0.64 cm) and ear perimeter (12.11±0.38 cm). Significant differences in ear length were noted between the RB65 and CM treatments, with the former showing superior results. However, no significant differences in ear perimeter were detected among the treatments. Regarding productive kernel number per ear and kernel weight per ear, the RB65 treatment again showed superior performance with 278.98±31.74 kernels per ear and a kernel weight of 91.22±7.85 g. Additionally, the highest 1000-kernel weight was observed under the RB65 treatment (319.33±13.6 g), followed by the RB110 treatment (305.67±2.08 g). Moreover, the analysis of LAI for irrigated maize, as depicted in Figure 5, reveals significant variability across different RB treatments throughout the growing season. The RB110 treatment consistently demonstrated the highest LAI, reaching its peak at 69 DAS. Conversely, the RB25 treatment consistently produced the lowest LAI values across all growth stages. The LAI values for RB65 and RB110 treatments were relatively close, with RB65 only slightly lower.

Table 2. Growth and yield-contributing characteristics of irrigated maize

Treatment	Plant height (cm)	Ear length (cm)	Ear perimeter (cm)	Productive kernel number per ear	Kernel weight per ear (g)	1000 kernel weight (g)
CM	224.167±38.81	16.92±0.75^{ab}	12.06±0.52	263.80±46.86	80.66±7.33	312.67±11.02
RB25	216.53±23.86	16.65 ±1.29^{ab}	11.82 ±0.31	262.38±29.23	79.5±10.8	302±23.58
RB65	219.08±29.96	17.385±0.64^{a}	12.11±0.38	278.98±31.74	91.22±7.85	319.33±13.6
RB110	212.81±31.80	15.6±0.46^{b}	11.81±0.28	240.07±25.18	72.04±17.8	305.67±2.08
Significance	NS	*	NS	NS	NS	NS
CV (%)	14.44	24.2	16.47	39.17	15	5.16
LSD$_{0.05}$	0.48	0.22	0.85	0.47	0.32	0.30

Note: Different letters, a and b, in results indicate a significant difference at a level of 0.05; asterisk symbol ‘*’ indicates that the difference among the data was statistically significant; CV, Coefficient of Variation; LSD, Least Significant Difference; NS, Non-Significant; CM, Conventional Method, and RB110, RB65, and RB25 denote Raised Bed (RB)-based irrigation methods with bed widths of 110 cm, 65 cm, and 25 cm, respectively

Table 3. Effect of various irrigation practices on grain yield, harvest index, and water footprints of cultivated maize

Treatment	Grain yield (t/ha)	Straw yield (t/ha)	Biological yield (t/ha)	Harvest index (%)	GWF (l/kg)	BWF (l/kg)	TWF (l/kg)
CM	9.89±1.11	21.01±2.16a	30.9±3.27	32.01±0.01b	117.24 ±13.35	92.45±10.52a	209.7±23.87a
RB25	11.96±1.7	17.545±0.47ab	28.51±2.15	38.31±0.03ab	105.807±15.83	82.7±12.37a	188.51±28.20ab
RB65	13.1±1.4	18.54±2.24ab	31.63±2.4	41.46±0.05a	88.6±10.07	12.63±1.43b	101.22±11.50c
RB110	10.35±3.77	16.06±2.17b	26.4±5.9	38.30±0.06ab	112.119±50.61	12.758±5.75b	124.87±56.37bc
Significance	NS	*	NS	*	NS	*	*
CV (%)	20.84	13.62	13.1	13.16	25.01	78.58	33.4
LSD 0.05	0.37	0.06	0.36	0.12	0.47	<0.001	0.016

Note: Different letters, a, b and c, in results indicate a significant difference at a level of 0.05; asterisk symbol ‘*’ indicates that the difference among the data was statistically significant. CV: Coefficient of Variation, LSD: Least Significant Difference, NS: Non-Significant, GWF: Green Water Footprint, BWF: Blue Water Footprint, TWF: Total Water Footprint, CM: Conventional Method, and RB110, RB65, and RB25 denote Raised Bed (RB)-based irrigation methods with bed widths of 110 cm, 65 cm, and 25 cm, respectively

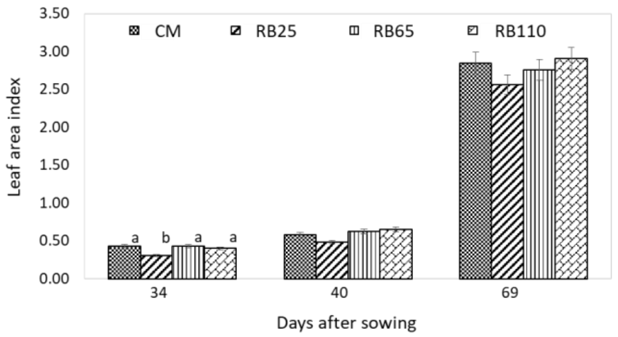

Figure 5. Comparison of leaf area index values for irrigated maize across different days after sowing using various irrigation techniques; error bars represent the standard deviation of the mean, and different letters (a and b) indicate a significant difference at the 0.05 significance level

Yield and Harvest Index (HI)

The study examined the impact of different irrigation methods on maize grain yield and HI, with detailed findings presented in Table 3. The RB65 method demonstrated the highest effectiveness, achieving a grain yield of 13.1±1.4 t/ha, significantly surpassing the yield of 9.89±1.11 t/ha observed with the CM. Additionally, the RB65 treatment resulted in the highest HI of 41.46±0.05%, indicating a more efficient conversion of biomass into grain yield compared to the significantly lower HI of 32.01±0.01% recorded for the CM method. The RB65 treatment also achieved the highest total biological yield at 31.63±2.4 t/ha, further underscoring its effectiveness. In contrast, the RB110 treatment, which utilized a 110 cm bed width, recorded the lowest straw yield (16.06±2.17 t/ha) and biological yield (26.4±5.9 t/ha). The CM treatment, however, showed an increased straw yield of 21.01±2.16 t/ha.

Water footprints of cultivated maize

The WF analysis presented in Table 3 reveals significant variations across different irrigation treatments for maize cultivation, offering valuable insights into WUE. The CM exhibited the highest TWF of 209.7±23.87 l/kg, indicating the least efficient water use. In contrast, the RB treatments showed markedly improved WUE, with RB65 demonstrating the lowest TWF of 101.22±11.50 l/kg, representing a reduction of over 50% compared to CM. The BWF results are particularly noteworthy, with CM showing the highest value of 92.45±10.52 l/kg, while RB65 and RB110 demonstrated significantly lower BWFs of 12.63±1.43 l/kg and 12.758±5.75 l/kg, respectively. Regarding the GWF, the study observed values ranging from 88.6±10.07 l/kg for RB65 to 117.24±13.35 l/kg for CM. The RB25 treatment recorded a GWF of 105.807±15.83 l/kg, while RB110 showed a GWF of 112.119±50.61 l/kg.

Water productivity with irrigation water-saving

The data presented in Figure 6 reveals significant variations in water productivity and irrigation water savings across different bed widths, emphasizing the advantages of RB systems. Notably, the RB65 technique demonstrated the highest water productivity, attributable to its optimal 65 cm bed width. This configuration improved water distribution while reducing losses through deep percolation and runoff. Regarding irrigation water savings, the RB110 system emerged as the most efficient, achieving a 37.72% reduction in water usage compared to the CM. Similarly, the RB65 system saved 36.12% of irrigation water. Conversely, the RB25 system achieved only a 0.386% water savings.

Relationships between maize productivity parameters under conventional and RB65 treatments

The RB65 technique has so far shown superior performance in maize productivity parameters compared to other RB dimensions. To explore this further, a correlation analysis was conducted (Table 4) to gain insights into the relationships between maize growth parameters under both CM and RB65 treatments. This analysis aimed to identify the key growth parameters affecting maize productivity in these treatments. In the CM treatment, plant height, ear length, and the number of productive kernels per ear showed strong positive correlations with grain yield and kernel weight per ear, highlighting their importance in determining maize productivity. Notably, plant height had a highly significant correlation with both grain yield ($r=0.999$, $p<0.01$) and kernel weight per ear ($r=0.999$, $p<0.05$), indicating that taller plants tend to yield more grain and heavier kernels. Additionally, the number of productive kernels per ear strongly correlated with grain yield ($r=0.999$, $p<0.05$) and kernel weight per ear ($r=0.997$, $p<0.05$), emphasizing kernel productivity as a crucial factor in maize yield under conventional irrigation. Under the RB65 treatment, correlation dynamics shifted due to the optimized water distribution and soil moisture. Although plant height still positively correlated with grain yield and kernel weight per ear, the strength of these correlations decreased ($r=0.679$ for grain yield and $r=0.923$ for kernel weight). Interestingly, ear length and the number of productive kernels per ear became more influential in this treatment. Ear length showed a very high correlation with grain yield ($r=0.997$) and straw yield ($r=0.991$). Moreover, the number of productive kernels per ear had even stronger correlations with grain yield ($r=0.999$) and straw yield ($r=0.999$). These results suggest that, under RB65, ear length and kernel number are more significant in driving overall productivity than plant height.

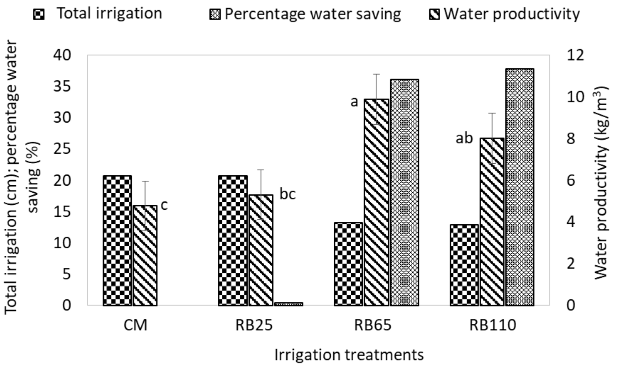

Figure 6. Water productivity and percentage of water savings for different irrigation techniques in maize cultivation; error bars represent the standard deviation of the mean, and different letters (a, b, and c) indicate significant differences at a 0.05 significance level

Table 4. Pearson correlation matrix (r) of maize parameters measured under (a) CM and (b) RB65 treatments

(a) CM treatment									
	PH	**EL**	**EP**	**PKNE**	**KWE**	**1000 KW**	**GY**	**SY**	**HI**
PH	1.000								
EL	0.940	1.000							
EP	0.731	0.455	1.000						
PKNE	0.999*	0.924	0.762	1.000					
KWE	0.999*	0.949	0.713	0.997*	1.000				
1000 KW	0.950	0.999*	0.481	0.935	0.958	1.000			
GY	0.999**	0.936	0.738	0.999*	0.999*	0.946	1.000		
SY	0.999*	0.956	0.696	0.995	0.999*	0.965	0.998*	1.000	
HI	0.858	0.632	0.978	0.881	0.844	0.655	0.864	0.831	1.000

Table 4. Continue

(b) RB65 treatment

	PH	EL	EP	PKNE	KWE	1000 KW	GY	SY	HI
PH	1.000								
EL	0.617	1.000							
EP	0.922	0.874	1.000						
PKNE	0.697	0.994	0.921	1.000					
KWE	0.923	0.872	0.999**	0.919	1.000				
1000 KW	0.720	0.990	0.933	0.999*	0.931	1.000			
GY	0.679	0.997	0.910	0.999*	0.909	0.998*	1.000		
SY	0.719	0.991	0.932	0.999*	0.931	0.999**	0.998*	1.000	
HI	0.462	0.983	0.770	0.958	0.768	0.948	0.965	0.949	1.000

Note: *Correlation is significant at the 0.05 level (2-tailed), **Correlation is significant at the 0.01 level (2-tailed), PH: Plant Height, EL: Ear Length, EP: Ear Perimeter, PKNE: Productive Kernel Number per Ear, KWE: Kernel Weight per Ear, 1000 KW: 1000 Kernel Weight, GY: Grain Yield, SY: Straw Yield, and HI: Harvest Index

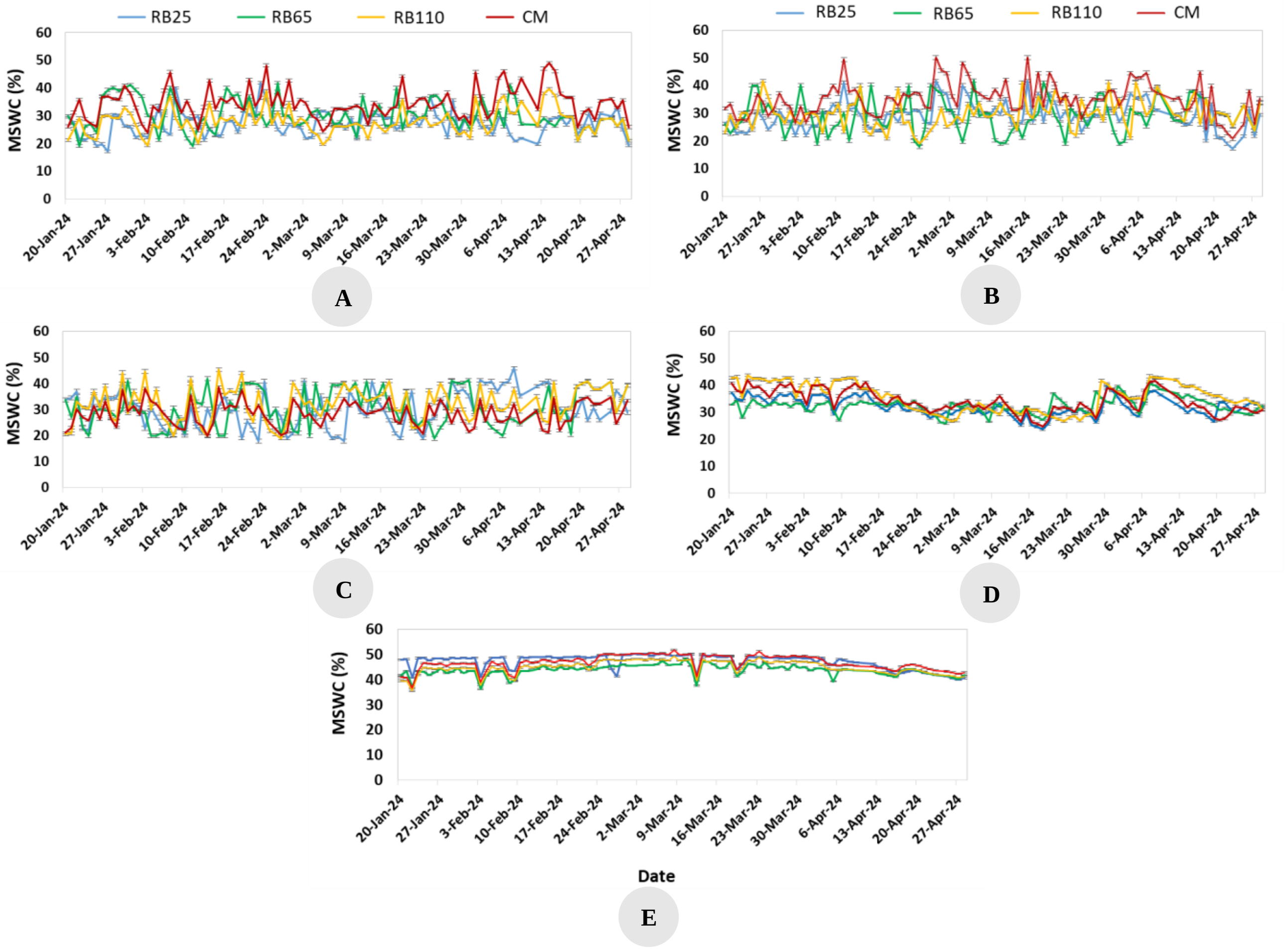

Figure 7. Comparison of mean soil water content (MSWC) across various irrigation treatments at different soil profile depths of A. 10 cm, B. 20 cm, C. 30 cm, D. 40 cm, and E. 80 cm during maize cultivation; error bars indicate the standard deviation of the mean

Effects of treatments on soil moisture content in irrigated maize field

The analysis of soil moisture dynamics across different RB treatments reveals significant variations in moisture retention at various soil depths (Figure 7), which are crucial for supporting healthy maize growth. At a depth of 10 cm (Figure 7.A), the RB65 treatment-maintained soil moisture levels that were sufficiently close to those of the CM treatment. Among these, the RB110 treatment retained the most moisture, followed by RB65 and RB25. At a 20 cm depth (Figure 7.B), the trend of higher soil moisture content in RB treatments persisted, with RB110 again showing the highest levels. As the depth increased to 30 cm (Figure 7.C), RB65 and RB110 demonstrated comparable soil moisture content, both significantly higher than RB25 and CM. Moreover, at 40 cm depth (Figure 7.D), RB110 continued to outperform other treatments in moisture retention, followed by RB65 and RB25. Finally, at 80 cm depth (Figure 7.E), RB110 maintained its advantage, retaining the highest soil moisture content among all treatments. The variation in soil moisture content across treatments can be partly attributed to the high rainfall observed during the initial and later stages of the crop growth period, coupled with uneven distribution throughout the crop cycle.

Discussion

Growth and yield-contributing attributes

The findings presented in Table 2 indicate that the CM treatment resulted in the tallest plants, suggesting that traditional methods may still have advantages in terms of overall plant height. However, the RB65 treatment's superior performance in ear length and perimeter highlights the potential benefits of RB systems in improving yield-contributing attributes, likely due to enhanced water management and nutrient availability. This aligns with findings by He et al. (2015), who noted that RB systems tend to improve ear length and perimeter. The minimal variation in plant height across treatments suggests that irrigation methods may have a limited effect on this particular growth parameter, as also observed by Brar (2013). Moreover, the RB65 treatment's superior kernel number per ear and kernel weight per ear are consistent with the results reported by Tanveer et al. (2014), who also found that RB planting systems enhance kernel numbers. The absence of significant differences in kernel weight across treatments, as noted by He et al. (2015), suggests a complex interaction between irrigation methods and yield attributes. The high 1000-kernel weight observed under the RB65 treatment corroborates the findings of Mehta et al. (2011), who reported similar improvements in 1000-kernel weight under RB planting.

The LAI analysis (Figure 5) reveals that the RB110 treatment's optimal leaf area expansion is likely due to its ability to retain and evenly distribute water, especially during critical growth phases. This finding is consistent with previous studies by Pan et al. (2019) and Duan et al. (2021). The consistently low LAI values in the RB25 treatment may be attributed to limitations in water and nutrient distribution, a notion supported by Kashif et al. (2018). The similarity in LAI between RB65 and RB110 treatments suggests that beyond a certain bed width, the benefits in LAI may plateau, as noted by Yigezu et al. (2021). Moreover, the observed increase in LAI during the final development stage across all treatments may reflect maize's physiological response to increased water demand during flowering and grain filling. This phenomenon is particularly evident in the RB110 treatment, where the bed's capacity to retain and distribute water contributes to a late-stage increase in LAI. These findings underscore the importance of bed width in influencing not only LAI but also other growth parameters, thereby contributing to higher yield potential under optimal irrigation management, as highlighted by Islam et al. (2022) and Munmun et al. (2024).

Yield and Harvest Index (HI)

The results clearly demonstrate that the RB65 method is significantly more effective in improving maize grain yield and HI compared to the CM. The RB65 treatment achieved a grain yield of 13.1±1.4 t/ha, surpassing the yield observed under CM. This outcome aligns with studies by Kaur and Kumar (2018) and Kaur and Kaur (2022), which also reported increased productivity using optimized RB methods. Additionally, the higher HI of 41.46±0.05% in RB65, compared to 32.01±0.01% in CM, indicates more efficient biomass conversion into grain yield. This finding is consistent with Mehta et al. (2011) and Tanveer et al. (2014), who noted substantial improvements in grain yield and HI with optimized bed dimensions. The RB65 treatment also demonstrated the highest total biological yield (31.63±2.4 t/ha), reinforcing its superiority in maximizing maize productivity.

In contrast, the RB110 treatment's lower straw and biological yields suggest that excessively wide beds may not be as effective for maize cultivation. Wider beds, while efficient at reducing water losses through runoff and evaporation, may disrupt the balance between plant population density and resource availability, such as water and nutrients. The RB110 treatment had fewer plants per unit area compared to RB65, leading to reduced biomass and grain yield. This supports the findings of Yigezu et al. (2021), who observed decreased crop productivity with overly wide beds due to inadequate plant populations and uneven water distribution. Furthermore, the increased straw yield in the CM treatment (21.01±2.16 t/ha) may be attributed to greater plant height under frequent irrigation, but the trade-off between grain and straw yield highlights the inefficiency of conventional methods. Overall, the RB65 treatment emerges as a more sustainable and productive alternative to CM, optimizing both water use and crop productivity (Pan et al. 2019; Duan et al. 2021).

Water footprints

The results presented in Table 3 clearly indicate that the RB65 treatment offers the most efficient water use among the irrigation methods studied. The substantial decrease in TWF for RB65, which reduced water use by over 50% compared to the CM method, aligns with previous studies that reported significant water savings through RB systems (Mekonnen et al. 2020; Chandra et al. 2023). This efficiency in water use is critical, particularly in regions facing water scarcity. The dramatic reduction in BWF for the RB treatments, especially the RB65 configuration, highlights the method's ability to optimize irrigation water use. This finding is consistent with research by Akbar et al. (2016) and Ismail et al. (2021), who reported similar reductions in water use with RB systems. The lower BWF observed in RB treatments suggests a more efficient use of irrigation water, crucial for sustainable agricultural practices. The variation in GWF across treatments, despite the assumption of constant green water use, underscores the importance of yield differences in water footprint calculations. This finding highlights the need to consider both water use and crop productivity when assessing the overall efficiency of irrigation systems, as emphasized by

Li et al. (2020) and Feng et al. (2021). The RB65 treatment's superior performance in both BWF and GWF suggests it offers an optimal balance between water conservation and yield enhancement, aligning with the findings of He et al. (2015), Yadav et al. (2018), and Munmun et al. (2024).

However, it is important to interpret these results within the study's limitations. The assumption of constant green water use across treatments may oversimplify the complex soil-plant-atmosphere interactions inherent in different irrigation regimes. Future studies should consider employing lysimeter experiments to provide more accurate measurements of crop evapotranspiration, runoff, seepage, and percolation losses, as suggested by Rodriguez et al. (2015), Mekonnen et al. (2020), Bhatt et al. (2021). The variability in WF results across treatments emphasizes the need for site-specific optimization of irrigation strategies. As noted by Chapagain and Hoekstra (2011) and Elbeltagi et al. (2020), factors such as local climate, soil characteristics, and crop varieties can significantly influence water footprints. While the RB65 treatment showed promising results in this study, its performance may vary in different agro-ecological contexts.

Water productivity with irrigation water-saving

The results clearly highlight the superior water productivity of the RB65 technique, which is likely due to its optimal bed width of 65 cm (Figure 6). This configuration enhances water distribution and reduces losses through deep percolation and runoff, aligning with findings by Akbar et al. (2016), who observed similar improvements in soil properties and water efficiency under comparable conditions. The inefficiency of traditional flood irrigation methods, as demonstrated by the CM's lowest water productivity, underscores the need for adopting more efficient irrigation practices, as highlighted by Islam et al. (2022). Moreover, the RB110 system's efficiency in achieving a 37.72% reduction in water usage further underscores the critical role of bed width in water conservation (Figure 6). The broader beds in the RB110 treatment required less irrigation due to fewer furrows, a finding that aligns with Yigezu et al. (2021), who emphasized the effectiveness of wider beds in reducing water consumption by minimizing uncropped areas. Similarly, the RB65 system's 36.12% water savings demonstrate its balance between water use efficiency and crop yield. On the other hand, the RB25 system's minimal water savings of 0.386% highlight the limitations of narrower beds, which require more frequent irrigation due to faster drying, as supported by Pan et al. (2019).

These findings underscore the effectiveness of wider RBs, particularly those with bed widths between 65-110 cm, in optimizing water productivity and conserving irrigation water. This approach represents a valuable strategy for sustainable agriculture in water-scarce regions. The results are consistent with studies by Ismail et al. (2021) and Shah et al. (2024), who reported similar benefits of RB techniques in enhancing water productivity and crop yields. Furthermore, Kaur (2011) and Asif et al. (2022) observed improved grain yield and water productivity in maize under RB systems, attributing these outcomes to enhanced root development, nutrient uptake, and water availability. In conclusion, this study contributes to the growing body of evidence that RB systems, particularly those with wider bed dimensions, are highly effective in improving water productivity and conserving irrigation water.

Relationships between maize productivity parameters

The correlation patterns in Table 4 indicate that, in the CM treatment, plant height directly influences grain yield and kernel weight. This aligns with Tanveer et al. (2014) and Kaur and Kumar (2018), who identified plant height as a key determinant of maize productivity under traditional irrigation. The strong positive correlation between plant height and grain yield in this study supports this relationship, suggesting that taller plants are generally more productive in the CM setup. In contrast, the RB65 treatment shows a different pattern where ear length and the number of kernels per ear have a greater impact on yield than plant height. The weaker correlation between plant height, grain yield, and kernel weight in RB65 indicates a shift in productivity dynamics. Instead, the correlation coefficients for ear length and kernel number per ear highlight their enhanced role in yield under the RB65 system. This observation aligns with Yigezu et al. (2021), who found that bed dimensions, particularly in RB systems, positively affect yield-contributing traits like ear length and kernel number. The results underscore RB65’s optimized water distribution, which favors traits that directly boost yield. Overall, the analysis shows the efficacy of RB65 in altering maize productivity: while plant height is crucial in conventional methods, RB65 prioritizes ear length and kernel productivity for higher yield. This supports Mehta et al. (2011), emphasizing that bed dimensions significantly influence crop productivity. The shift in productivity dynamics suggests that RB65 can optimize water and nutrient distribution, offering a promising strategy for maize cultivation, especially in water-scarce regions. Further research on different RB dimensions could refine sustainable agricultural practices across various conditions. The evidence here suggests that adopting the RB65 method can enhance maize yield and water use efficiency, providing a significant advantage over traditional irrigation methods.

Soil moisture dynamics

The results in Figure 7 highlight the superior performance of RB65 in retaining soil moisture at different depths, likely due to its optimized bed width, which promotes water infiltration and minimizes evaporation. Wider beds, such as RB65, enhance the surface area for water percolation, leading to greater moisture retention within the soil profile. This aligns with the findings of Verhulst et al. (2011), who observed that optimized raised beds reduce surface runoff and improve infiltration, thus increasing moisture retention. Research has shown that RB systems, especially those with intermediate to wider bed widths like RB65 and RB110, are effective in maintaining higher soil moisture levels at deeper profiles. Yadav et al.

(2018) and AbdelRahman and Arafat (2020) similarly reported that wider beds reduce runoff and enhance water infiltration, improving soil moisture dynamics. Kaur et al. (2024) also found that wider bed configurations tend to retain more moisture compared to narrower ones, particularly at deeper soil levels. The increased moisture retention observed in deeper layers, especially at 40 cm and 80 cm, highlights the importance of improved infiltration and reduced evaporation, a characteristic that wider beds like RB110 offer. Studies by He et al. (2015) and Munmun et al. (2024) further support this, demonstrating that wider beds are more effective in retaining soil moisture, which is crucial for sustaining crops during periods of water scarcity. The RB110 system's ability to retain moisture in deeper soil layers is especially important for supporting maize root systems during drought conditions, as also noted by Duan et al. (2021), who emphasized the role of wider beds in enhancing crop resilience under water-limited conditions.

However, the additional moisture retained at deeper layers in RB110 may not always be advantageous. Maize typically has a rooting depth of around 60 cm, and thus the excess water retained at depths beyond this may not be fully utilized by the plant, especially during critical growth stages such as flowering and grain filling. As a result, while RB110 excels in moisture retention, this does not necessarily translate into better water use efficiency or higher crop yields. Verhulst et al. (2011) and He et al. (2015) emphasized that moisture distribution within the root zone is more critical for crop productivity than the total amount of water retained in the soil.

In contrast, the RB65 configuration, with its narrower bed width, offers a more balanced distribution of moisture, keeping water accessible within the root zone. This supports better crop growth, particularly during the grain-filling stages. The RB65 system's ability to retain soil moisture at optimal levels across various depths ensures better water distribution and supports higher grain yields and water use efficiency. Moreover, the reduced efficiency observed in the narrower RB25 and excessively wide RB110 treatments suggests that extreme variations in bed width do not provide the balance necessary for effective irrigation management. Selecting the appropriate bed width, such as the RB65 configuration, emerges as a promising technique for achieving sustainable maize cultivation, particularly in regions facing water scarcity. The RB65 system not only optimizes water retention but also maximizes yield and WUE, presenting a valuable strategy for sustainable agriculture.

Overall, this study highlights the critical role of RB dimensions in optimizing maize yield, WF, and soil moisture content under furrow irrigation. Among the tested configurations, the RB65 setup emerged as the most effective, significantly boosting yield and water productivity while reducing irrigation water use by 37.72%. It also maintained optimal soil moisture at various depths, ensuring efficient water distribution and retention—key advantages for regions facing water scarcity. Although the RB110 treatment demonstrated superior water retention, it underperformed in yield due to lower plant density and inefficient water utilization. In contrast, RB65 achieved a balance between moisture retention and crop yield by maintaining higher plant density and improving water distribution within the maize root zone. These findings emphasize the limitations of overly wide RB configurations like RB110 and the importance of carefully selecting bed widths to optimize water efficiency and crop productivity. The RB65 technique presents a promising solution for enhancing agricultural efficiency and resilience in water-scarce areas. For future studies, more precise WF estimations should incorporate crop evapotranspiration measurements and lysimeter experiments, and long-term research on different RB dimensions across various crops and soil conditions will be essential for refining sustainable agricultural practices. This research provides valuable insights for policymakers and farmers aiming to implement water-saving irrigation techniques to support agricultural sustainability in water-limited environments.

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