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EFFECT OF DRIP IRRIGATION ON YIELD AND WATER-USE EFFICIENCY IN FIVE DIFFERENT CROPS IN RWANDA

Nkundabashaka V[1]*, Ave MT[1], Niyonkuru R[1], Bugenimana DE[1], Rukera Tabaro S[1], Ndahetuye JB[1], Musemakweri JV[1] and C Kayijuka[1]

Nkundabashaka Valens

*Corresponding author email: nkuvalens@gmail.com
ORCID: https://orcid.org/0009-0000-1806-0771

[1]University of Rwanda (UR), College of Agriculture, Forestry and Food Sciences (CAFF), Rwanda

ABSTRACT

Agricultural productivity in Rwanda's semi-arid regions is increasingly challenged by intensified climatic variability, characterized by erratic rainfall, rising evapotranspiration, and recurrent dry spells. These conditions extremely affect agricultural production of different crops. These challenges undermining food security in a country where agriculture supports over 40% of the population. This study integrates two complementary experimental evaluations conducted across two growing seasons in semi-arid regions in Huye district. The research was conducted to assess the influence of drip irrigation management on dry matter yield (DMY) and Water-use Efficiency (WUE). Five key crops: Irish potato, maize, soybean, common bean, and Brachiaria grass were evaluated under both rainfed and drip irrigated system to assess their responsiveness to supplemental irrigation and their resilience to climatic stress, with consideration of their physiological classifications as C_3 and C_4 species. Across both season 1 and 2 drip irrigation showed highly significant effect on DMY and WUE with strong interaction effects between crop species and irrigation management at ($P<0.05$). Maize exhibited the strongest yield response to irrigation, achieving up to 58.2% yield improvement in Season 1 and maintaining the highest irrigated DMY of 8,334 kg/ha. It also demonstrated superior WUE of 22.6 kg/ha/ mm of DMY confirming its suitability in semi-arid environments. Brachiaria grass, although exhibiting smaller absolute yield increase under irrigation compared to maize crops. It consistently achieved the highest water-use efficiency (WUE) across all treatments, reaching up to 35.2 kg /ha/mm of DM thereby underscoring its strong physiological resilience in semi-arid environment. In contrast, Irish potato remained the least efficient crop under water-limited conditions, recording WUE as low as 7.0 kg/ha/mm of DM confining it as high- drought sensitivity crop in the region.

The findings highlight the importance of precision irrigation on different crops for increasing yields and efficient use of scarce water in semi-arid area of Rwanda. These results support effective water management as a key pillar for sustainable intensification and long-term food system stability in Rwanda, which is in line with the country's PSTA 4, NST2, and Vision 2050 goals.

Key words: Dry matter yield, water-use efficiency, semi-arid region, Drip irrigation

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INTRODUCTION

Agriculture Productivity in the semi-arid region of Rwanda is decreasing due to erratic rainfall and extended dry spells attributed to climate chang[1].These climates shifts have affected the yields for water-sensitive crops like beans, maize, and Irish potato. The National Institute of Statistics of Rwanda reported that 43.7% of the population was employed in the agriculture sector during the first quarter of 2025, confirming the essential role of agriculture in the economy of the country[2]. Sustaining water-use efficiency (WUE) through crop choice and proper irrigation management are the pillars of sustainable food security, ensuring sufficient agricultural production to meet national food needs and enabling farmers to produce enough for their own household consumption, thereby enhancing their resilience and well-being

The WUE is defined as the ratio of actual yield (kg/ha) to water consumption during the season (mm) [3]. Soybeans and Beans require less water due to their moderate root depth and nitrogen fixation capacity [4], hence necessitating shorter irrigation intervals [5].

Furthermore, Brachiaria grass exhibits great tolerance to water stress through its deep rooting system [6]. Most crops are extremely sensitive to water during periods of flowering [7], thus requiring precise irrigation management to prevent yield loss[8]. To establish a strong theoretical foundation for WUE conclusions, the varying physiological mechanisms among crops significantly dictate their productivity and WUE under water stress conditions [9]. The selected crops include C4 plants, such as Maize and Brachiaria grass, which possess high inherent water-use efficiency due to the C4 photosynthetic pathway, enabling them to achieve superior DMY and WUE, particularly under semi-arid conditions [10] . Conversely, C3 crops (such as Irish potato and Soybeans) are susceptible to yield reduction during critical water-sensitive phases highlighting the importance of efficient crop selection and irrigation management tailored to semi-arid environments[11].

Research conducted in Bata, Ethiopia on fodder crops proved that precise irrigation scheduling and crop selection enhance DMY and water productivity, helping farmers to adapt to climate variation [12]. Furthermore, studies conducted in Bugesera and Huye Districts of Rwanda showed that integrated water and crop management improves WUE and mitigates dry spells related impacts [11].

Over the past few decades, the frequency of dry spells has surged by approximately 30%, significantly exacerbating water stress during the most vulnerable and critical phases of crop development[14]. This trend poses a serious challenge to agricultural productivity and underscores the urgent need for adaptive water management

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strategies [15]. The climate projection for Rwanda expects increased dry spells by 2050 due to variability in rainfalls [16].

Given the different physiological mechanisms for C4 and C3 crops and the crucial role of precision irrigation management. This study examines the effects of drip irrigation management on five distinct crops (Irish potato, Maize, Soybeans, Beans, and Brachiaria grass) in the semi-arid region of Rwanda to ensure food security at the national level and household consumption through sustainable agricultural water management.

MATERIALS AND METHODS

This research employed rigorous field procedures and analytical methods across two growing seasons to evaluate the effects of drip irrigation management on agricultural production and water WUE in a semi-arid environment of Rwanda. The methodology prioritized precision in experimental design, water application, and the comprehensive assessment of water-use efficiency, enhancing the reproducibility and scholarly value of the findings.

Study Site and Experimental Design

The study was conducted at the University of Rwanda's farm in Huye District, Tonga village, Rwanda, which is situated between 1600 and 1800 meters above sea level. The fixed impacts of two main factors: water management (irrigated (I) and rainfed (R) conditions with five different crops (common bean, Brachiaria grass, Irish potato, maize, and soybean) were evaluated using a factorial experimental design.

A Completely Randomized Block Design (CRBD) was utilized, consisting of four uniform blocks, each block has 10 plots that represent all treatments combinations. All plots were standardized to a size of 6m × 8m. A 1m space was maintained between adjacent plots, and a 2m space separated the blocks to prevent lateral water movement.

Prior to sowing, 20 mm of water was applied uniformly to all plots (both irrigated and rainfed) to raise the soil moisture status to field capacity. This ensured that moisture depletion was effectively 0 mm at the sowing date. The decision to apply water before sowing was based on soil moisture measurements which indicated that the topsoil was below field capacity due to limited pre-season rainfall. During the crop establishment phase (2 weeks) after planting there was no additional irrigation because sufficient rainfall was received to support germination and emergence across seasons. Applying water prior to sowing standardized initial soil moisture conditions across all treatments, ensuring that subsequent comparisons between irrigated and rainfed plots reflected the effects of irrigation during the growing season rather than differences in crop establishment.

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Drip irrigation was utilized in the irrigated plots to ensure controlled water distribution. Daily meteorological inputs were recorded using an on-site meteorological station, and Daily meteorological inputs (rainfall, temperature, humidity, wind speed) were recorded using an on-site meteorological station, while soil moisture content was monitored dynamically using a PR2 moisture profile probe at multiple depths. The recorded data were integrated into simplified water balance equation to determine soil moisture changes within the soil profile. Rainfall measurements quantified natural water input, while evapotranspiration was estimated using climatic data through the FAO Penman-Monteith method. The real-time soil water content at various depths was obtained via PR2 probe readings, which were utilized to calculate changes in soil water balance to validate and modify irrigation scheduling. Experimental Layout is illustrated in figure1.

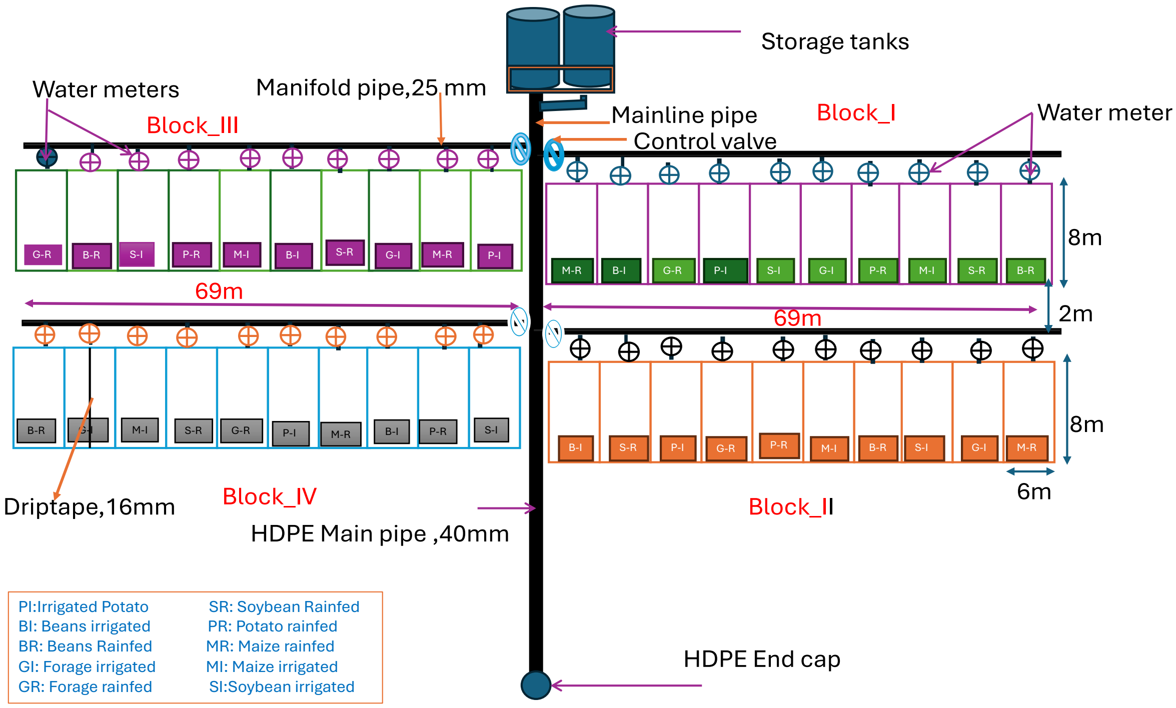

Figure 1: Experimental layout

Soil sampling and fertilizer application

Prior to sowing the soil samples were collected at five depths (0–100 cm) to analyze physical and chemical properties, including texture, Bulk Density (BD), water retention, pH, Total Nitrogen (TN), Soil Organic Carbon (SOC), Phosphorus (P), and Potassium (K). Referring to USDA soil field methods handbook[17]. In-situ standard field capacity (θ FC) was assessed for each block to confirm the reliability of the soil's water holding capacity. The assessment process involved clearing a plot 1.5m×1.5m and saturating it to 100%, plots were then covered with a black plastic sheet for three days to allow water drainage through soil profile. Measurements were taken using a moisture meter and found that final average moisture (%) recorded during this assessment ranged from 22.9% to 23.1% confirming soil texture as sandy loam. The SPAW model developed Saxton et al.[18] was used to estimate Wilting Point. The model used organic matter and soil texture data as its main input data to estimate soil water content at a tension of -1500 kPa, which represents the point at which plants can no longer extract water. Soil characteristics are detailed in Table1. Fertilizers (DAP, KCL, UREA, NPK) were applied based on nutritional needs and local conditions. Nitrogen is vital for growth and protein synthesis, while Phosphorus supports root development and energy transfer, especially in acidic soils where its availability is often limited. The selected fertilizers ensure adequate Phosphorus to facilitate flowering and seed formation. Potassium plays a key role in water regulation and stress tolerance, crucial for high-energy crops like Irish potato and Brachiaria grass. Given the low native soil fertility and high acidity, balanced N, P, and K fertilization is essential to maximize crop yields. Application rates are detailed in Table 2.

Climatic data collection and water balance

Daily Climatic data were collected from local weather station and used to calculate ETo through Penman Monteith model procedures**.** Precise irrigation scheduling following the initial establishment phase relied on a dynamic water balance approach derived from FAO Paper 56 guidelines[19]. The experimental site's deep groundwater table (>1m), sandy loam texture and proper irrigation management ensured that runoff and capillary rise were negligible and simplify the water balance calculation. Subsequent irrigation events were scheduled when the soil moisture depletion approached the crop-specific stress threshold, defined by the Readily Available Water (RAW). Rooting depth (Z r) for each crop was estimated in-situ from uprooted roots following harvest, which informed the calculation of water availability as summarized in table 3.

The following equations were utilized to determine water balance and irrigation scheduling across the selected crops. The amount of I(mm) and RAW (mm) are represented in figure 2.

$ETc = ETo \times Kc$ …………………………………………….(1)

Where ETc stands for crop evapotranspiration, ETo stands for reference evapotranspiration and Kc stands for crop coefficient.

$SWDi = SWDi\text{-}1 + ETci - Ii - Pi$ ……………………….(2)

Where SWDi is soil water depletion, ETci is adjusted crop evapotranspiration, Ii stands for irrigation, Pi stands for precipitation.

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$TAW = 1000\ (\theta FC - \theta WP) \times Zr$ ……………………………..(3)

Where TAW is total available, θFC is field capacity and θWP is wilting point.

$RAW = p \times TAW$ ……………………………………….…..(4)

Where RAW is readily available water and p is depletion fraction

$Ks = (TAW - Dr) / (1 - p) \times TAW$ …………………………(5)

Where Ks is water stress coefficient and, Dr is root zone depletion.

$ETc\ adj = Ks \times Kc \times ETo$ ……………………………….(6)

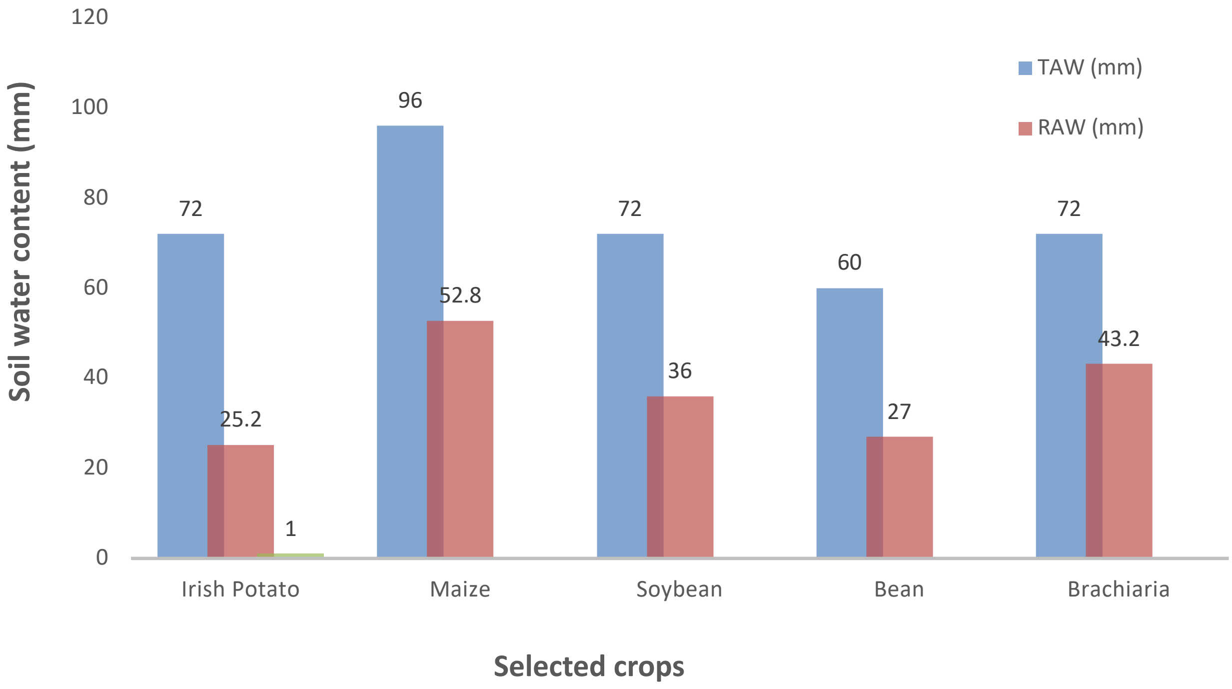

Figure 2: Soil water parameters considered for irrigation planning across seasons

Yield measurement and water-use efficiency

Fresh Yield (FY) and WUE were assessed at harvest by sampling in the four inner rows of each plot. Samples were analyzed at the Rwanda Agriculture and Animal Resources Development Board (RAB) laboratory to determine dry matter percentage (DM%) used to calculate DMY.

WUE was computed using two approaches to provide a comprehensive evaluation of crop performance and water management efficiency. $WUE_{(ETc)}$, was based on actual crop evapotranspiration and calculated as in equation and $WUE_{(P+I)}$ based on total water input (precipitation and irrigation). The following questions were used to calculate the above metrics.

$$DMY\left(\frac{kg}{ha}\right) = \text{FY(Kg/ha)} \times \text{DM (\%)} \text{ ....(1)}$$

where DMY represents dry matter yield, FY stands for fresh yield (marketable yield at harvest)

$$WUE(ETc) = \frac{DMY\left(\frac{kg}{ha}\right)}{ETc\ (mm)} \text{ ....(2)}$$

Where $WUE(ETC)$ stands for water-use efficiency based on actual crop evapotranspiration

$$WUE(P + I) = \frac{DMY\left(\frac{kg}{ha}\right)}{P+I(mm)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3)}$$

Where WUE (P+I) stands for water-use efficiency based on total water input (irrigation and precipitation)

Statistical Data analysis

A two-way Analysis of Variance (ANOVA) was used to examine the fixed effects of water management (irrigated and rainfed), selected crops and their interaction on water-use efficiency based on evapotranspiration (WUE $_{(ETc)}$) and water-use efficiency based on total water supplied (WUE$_{(I+P)}$). Estimated marginal means (EMMs) were computed for each treatment crop combination and pairwise comparisons were performed using Tukey-adjusted p-values to identify significant differences. Standard errors and 95% confidence intervals were calculated to ensure precision. This analysis provided a clearer interpretation of water management effects on water-use efficiency among the selected crops across two growing seasons. The analysis was performed using R-software models. Statistical analyses were performed using software models and significance was declared at ($p < 0.05$).

RESULTS AND DISCUSSION

Climatic variations across seasons

Analysis of seasonal climate data revealed significant shifts in temperatures, relative humidity, solar radiation wind speed and ETo between the two growing seasons. Season 1 recorded slightly higher average maximum temperatures (23.5°C) compared to Season 2 (22.2°C), while minimum temperatures were similar (13.9°C vs. 13.7°C). Relative humidity was marginally higher in Season 2 (79.7%) than in Season 1 (78.7%), indicating a more humid environment. Solar radiation increased from 16.6 MJ m^{-2} day^{-1} in Season 1 to 18 MJ m^{-2} day^{-1} in Season 2. Seasonal variations in ETo offer a more accurate representation of atmospheric demand.

Comparing ETc, which takes Kc into account, gives an even more realistic picture of how much water crops consume across the seasons. Wind speed also rose slightly from 2.4 m s^{-1} to 3 m s^{-1}, further contributing to evaporative demand. Consequently, ETo showed a marginal increase from 3.3 mm day^{-1} in Season 1 to 3.4 mm day^{-1} in Season 2. This indicates that elevated solar radiation and wind speed in Season 2 offset the moderating effect of higher humidity, creating a high evapotranspiration environment that could influence crop water use and growth dynamics. Average climatic data for season1 and 2 are summarized in tables 3 and 4, respectively.

Water balance and irrigation planning

The analysis of soil moisture dynamics across two growing seasons revealed a distinct contrast between irrigated and rainfed treatments for all five crops: Irish Potato, Maize, Soybean, Bean, and Brachiaria. Soil moisture depletion was calculated using a simplified water balance equation and monitored via a PR2 soil moisture profile probe, which serves as a critical indicator of water availability in the soil profile across the two growing season 1 and as represented in tables 5 and 6, respectively.

In Season 1, irrigated plots maintained significantly more stable moisture profiles compared to rainfed plots. For instance, moisture depletion in irrigated Irish Potato and Maize remained controlled, whereas rainfed counterparts exhibited drastic depletion, frequently approaching levels near -60.0 mm as illustrated in the figures 3and 4, respectively. Similarly, in Season 2, the data confirms that drip irrigation effectively mitigated the severe moisture deficits observed in rainfed systems as illustrated in the figures 5 and 6, respectively. The rainfed crops for Season 2, particularly Brachiaria and Soybean, showed deep depletion curves, indicating that these crops were forced to extract limited water from deeper soil profiles to survive, whereas the irrigated crops benefited from consistent moisture replenishment.

The primary scientific principle driving these results is the reduction of plant water stress through localized application. Drip irrigation delivers water directly to the root zone, maintaining soil moisture at or near field capacity. This prevents the soil from reaching the permanent wilting point, a condition evident in the rainfed plots where depletion levels dropped sharply. By using a PR2 soil moisture profile probe, we observed that drip irrigation ensures a consistent vertical moisture gradient, which is essential for nutrient solubility and uptake.

When soil moisture depletion is minimized, the plant does not need to close its stomata to conserve water. This allows for continuous transpiration and CO2 exchange, which are the fundamental drivers of photosynthesis. In contrast, the high depletion levels seen in the rainfed data suggest that those crops experienced stomatal closure, leading to reduced biomass accumulation and, consequently, lower yields.

The observed stability in soil moisture directly correlates with the WUE and overall yield of the five crops in the Rwandan context. By maintaining moisture depletion within an optimal range (as seen in the irrigated graphs), the crops were shielded from the erratic rainfall patterns typical of the region. This stability ensures that the energy of the plant is directed toward reproductive growth yield rather than stress mitigation.

Drip irrigation maximizes WUE by minimizing the losses side of the water balance equations specifically reducing surface evaporation and deep percolation. Because the water is applied precisely, a higher percentage of the applied water is used for transportational growth rather than being lost to the environment.

In conclusion, the use of drip irrigation in Rwanda for these five specific crops provides a buffered environment that prevents the extreme soil moisture depletion seen in rainfed systems. This precision management, verified by the PR2 probe data, is the key factor in achieving superior yields and high-water productivity, making it a vital strategy for food security in the face of climate variability.

The analysis of soil moisture dynamics across two growing seasons reveals a distinct contrast between irrigated and rainfed treatments for all five crops: Irish Potato, Maize, Soybean, Bean, and Brachiaria. Soil moisture depletion, calculated using a simplified water balance equation and monitored via a PR2 soil moisture profile probe, serves as a critical indicator of water availability for Y and WUE maximization.

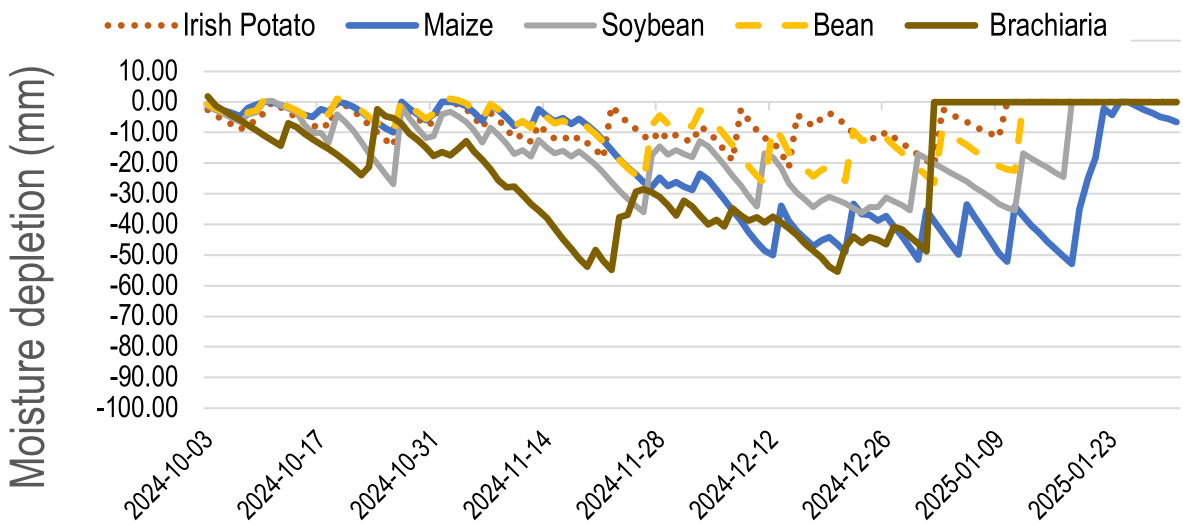

Figure 3: Soil moisture depletion in irrigated plots during season 1

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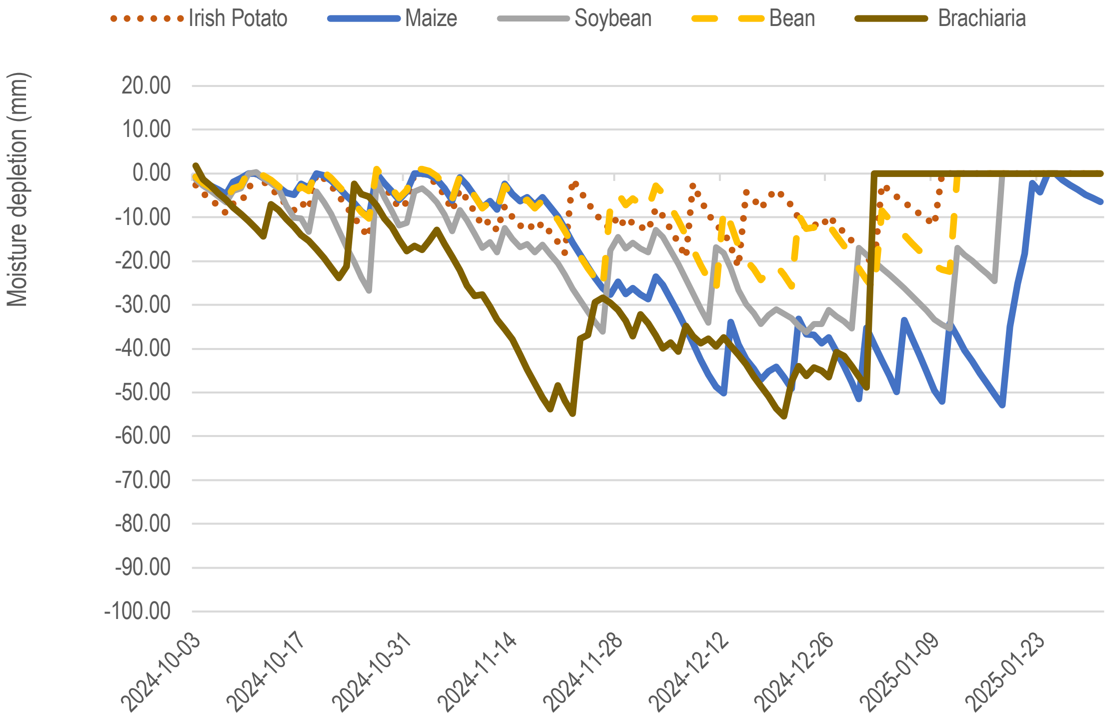

Figure 4: Soil moisture depletion in rainfed plots during season 1

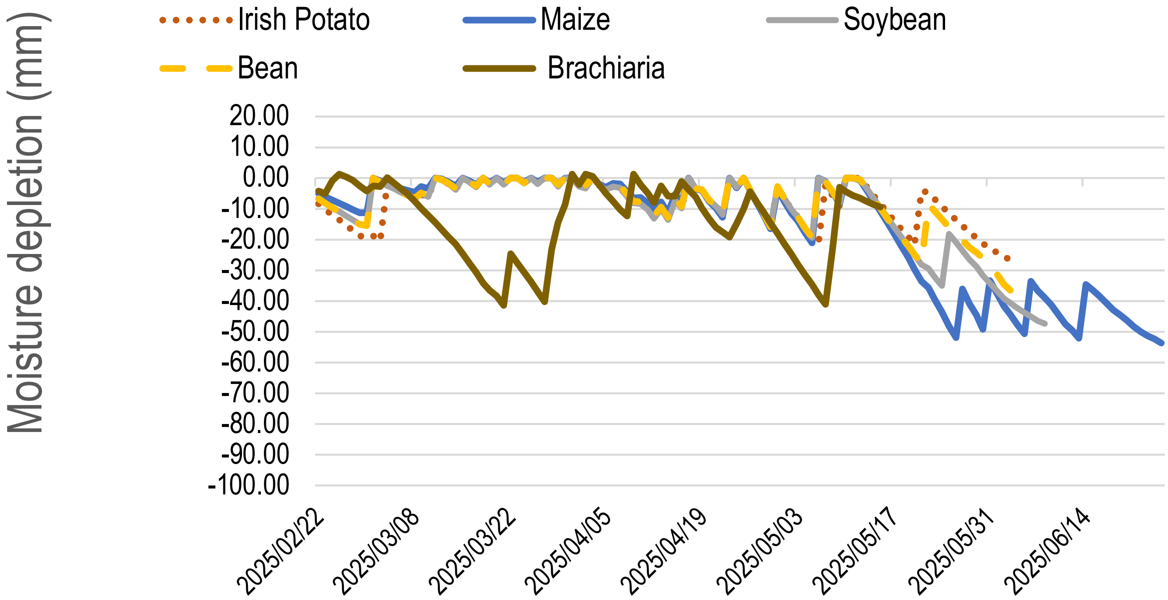

Figure 5: Soil moisture depletion in irrigated plots during season 2

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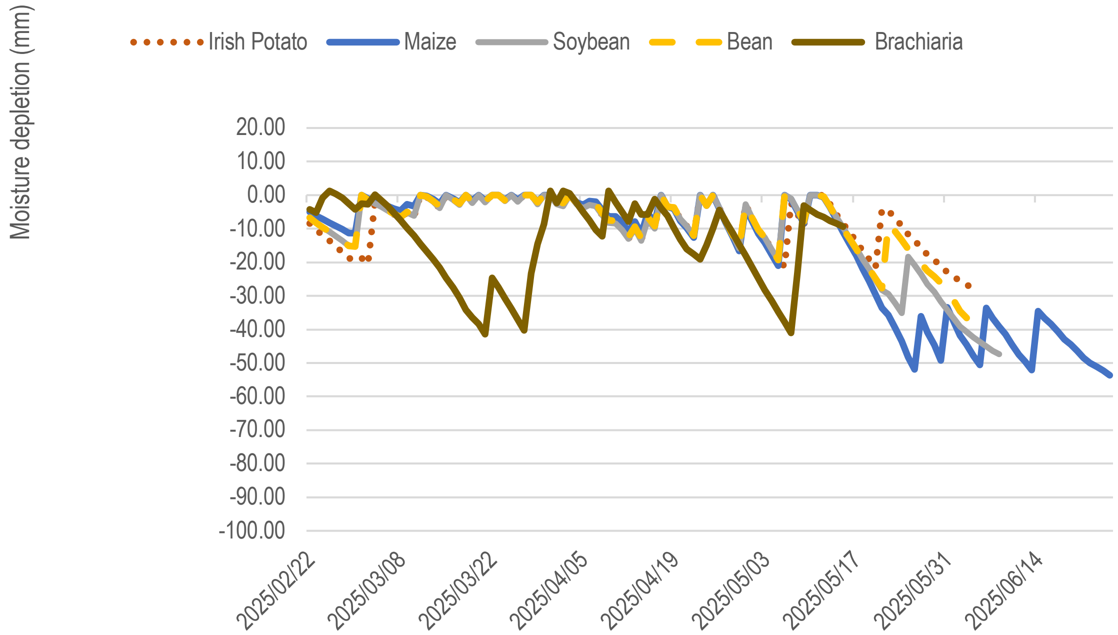

Figure 6: Soil moisture depletion in rainfed plots during season 2

Due to high precipitation received during the second season this abundance, the contribution of irrigation to the total water supply in Season 2 was minimal, dropping to just 3.31% for beans. Conversely, Season 1 was drier, making irrigation essential; here, irrigation shares ranged from a low of 13.514.0% for Brachiaria grass to a high of 32.91% for Maize. These seasonal contrasts emphasize that while crops such as Brachiaria grass and beans demonstrate resilience under rainfed conditions, water-sensitive crops like maize and Irish potato necessitate supplemental irrigation to mitigate dry spell impacts.

Dry Matter Yield

The outcomes of DMY cross season1and2 indicated that irrigation had a significant impact as summarized in the tables 7and 8 respectively. Season 1 yielded 5268.5 kg/ha from rainfed plots and 8,333.5 kg/ka from irrigated plots. This is a 3065.0 kg/ha increase and a 58.2% percentage increase. In Season 2, irrigated plots produced 8071.7 kg/ha, up 1975.3 kg/ha and 32.40% from rainfed conditions, which produced 6096.4 kg/ha. Brachiaria significantly improved when irrigated. Irrigation boosted yields by 983.0 kg/ha, or 20.19%, in the first season.

In Season 2, rainfed plots produced 5094.8 kg/ha, whereas irrigated plots produced 7571.1 kg/ha, a 48.6% increase and 2476.3 kg/ha. Bean responded positively to irrigation. In Season 1, irrigated plots yielded 4930.7 kg/ha while rainfed plots produced 3290.1 kg/ha. This is an increase of 1640.6 kg/ha and a gain of 49.9%. In

Season 2, irrigation added 722.0 kg/ha to the yield, which represents a gain of 17.7%. Irish potato also benefited from irrigation. In Season 1, irrigated plots produced 1840.9 kg/ha compared to 1237.7 kg/ha under rainfed conditions. This is an increase of 603.2 kg/ha and a gain of 48.73 %. In Season 2, irrigation added 349.3 kg/ha to the yield, which corresponds to a gain of 25.0%. Soybean showed consistent improvement with irrigation. In Season 1, irrigated plots yielded 4851.2 kg/ha while rainfed plots produced 3736.2 kg/ha.

This represents an increase of 1115.0 kg/ha and a gain of 29.84 %. In Season 2, irrigated plots produced 1975.3 kg/ha this represents the increases of 32.4%. Irrigation helps prevent plants from reaching their permanent wilting point, keeps stomata open, and sustains CO2 uptake and photosynthesis leading to improved dry matter production. Drip Irrigation helps prevent plants from reaching their permanent wilting point, keeps stomata open, and sustains CO2 uptake and photosynthesis leading to improved dry matter accumulation.

The experimental results indicate that irrigation improves crop yields, supporting the Strategic Plan for Agriculture Transformation (PSTA 4) that advocates for a shift from subsistence to commercial production. In Rwanda, irrigation facilitates the transition from rain-fed farming to more diverse, high-value crops, enhancing cropping intensity and land productivity.

Maize has shown a significant positive response to irrigation, with yields reaching about 4,450 kg/ha due to enhanced management practices and appropriate input usage. Moisture supply is crucial for yield, as moisture stress during critical growth phases hampers productivity. To address climate-related challenges, the government has focused on achieving self-sufficiency in maize seed supply, eliminating subsidies on imported seeds by developing high-yield hybrid varieties.

Brachiaria has demonstrated significant benefits under irrigation as a forage crop, providing year-round green foliage and thriving in low-rainfall regions. It addresses feed shortages in mixed crop-livestock systems during the dry season, which contribute to low livestock productivity. Irrigation for fodder ensures a reliable supply of nutritious biomass, crucial for cattle health and can enhance milk yields by up to 50%.

Beans and soybeans exhibited positive responses to irrigation, enhancing food and nutrition security by increasing pulse yields. Research shows that moisture and heat stresses limit legume production, and irrigated systems can mitigate these issues. This transition also supports the goal of achieving self-sufficiency in seeds supply for oil crops.

Irish potato cultivation in Rwanda has benefited from irrigation as part of the Crop Intensification Program (CIP), aimed at enhancing yields and reducing post-harvest losses. With effective water management and improved seed varieties from the International Potato Center, yields can reach 25,000-35,000 kg/ha of fresh yields as reported by Magruder & Ndahimana[20]. This shift to irrigated agriculture has increased cropping intensity, achieved a 30% mechanization rate, and contributed to a 5% growth in Agri-GDP. These improvements are essential for realizing the goals of Vision 2050, which aspires for enhanced living standards and quality of life for Rwandans.

Water-use efficiency across seasons

The Water-use Efficiency (WUE) calculated based on actual evapotranspiration (), demonstrated distinct variations across the five selected crops during the two growing seasons (Figure 7). Brachiaria and Maize exhibited the highest efficiency under irrigated conditions, recording values of 21.3 kg/ha/mm and 20.0 kg/ha/mm, respectively. In contrast, Irish potato showed the lowest at 6.6 kg/ha/mm under irrigation and 5.4 kg/ha/mm under rainfed conditions. Across all crops, irrigated systems consistently achieved higher WUE compared to rainfed systems, with Brachiaria maintaining its lead in rainfed efficiency at 15.6 kg/ha/mm.

When evaluating WUE based on total water input (precipitation + irrigation, or P+I), the trends remained consistent with metrics, although the absolute values were generally higher (Figure 8). Brachiaria outperformed all other crops significantly, reaching a peak WUE (P+I) of 35.2 kg/ha/mm under irrigation and 30.5 kg/ha/mm in rainfed plots, Maize and Bean followed, with irrigated Maize reaching 22.6 kg/ha/mm and irrigated Bean at 18.1 kg/ha/mm, Like the results, Irish potato recorded the lowest efficiency in total water utilization, with values of 7.9 kg/ha/mm (irrigated) and 7.4 kg/ha/mm (rainfed).

The results indicate that irrigation management plays a critical role in enhancing water productivity across different crop types. The consistently higher WUE in irrigated treatments (Figures 7 and 8) suggests that controlled water application optimizes the crop's physiological processes better than relying solely on erratic rainfall. The substantial performance of Brachiaria in both metrics highlights its superior ability to convert both consumed water () and total available water (P+I) into biomass, making it the most water-efficient crop among those studied.

The narrow margin between irrigated and rainfed WUE (P+I) for crops like Maize (22.6 vs 22.0 kg/ha/mm) and Bean (18.1 vs 17.3 kg/ha/mm) suggests that while irrigation increases absolute yield, the efficiency of total water input remains relatively stable for these specific crops, Conversely, the significant drop in for Brachiaria when moving from irrigated (21.3 kg/ha/mm) to rainfed (15.6 kg/ha/mm) conditions indicates that this crop is particularly responsive to supplemental irrigation in terms of its actual water consumption. The low WUE of Irish potato across all categories suggests it may have a higher water requirement or lower drought tolerance compared to the cereals and legumes studied, resulting in less biomass production per millimeter of water used.

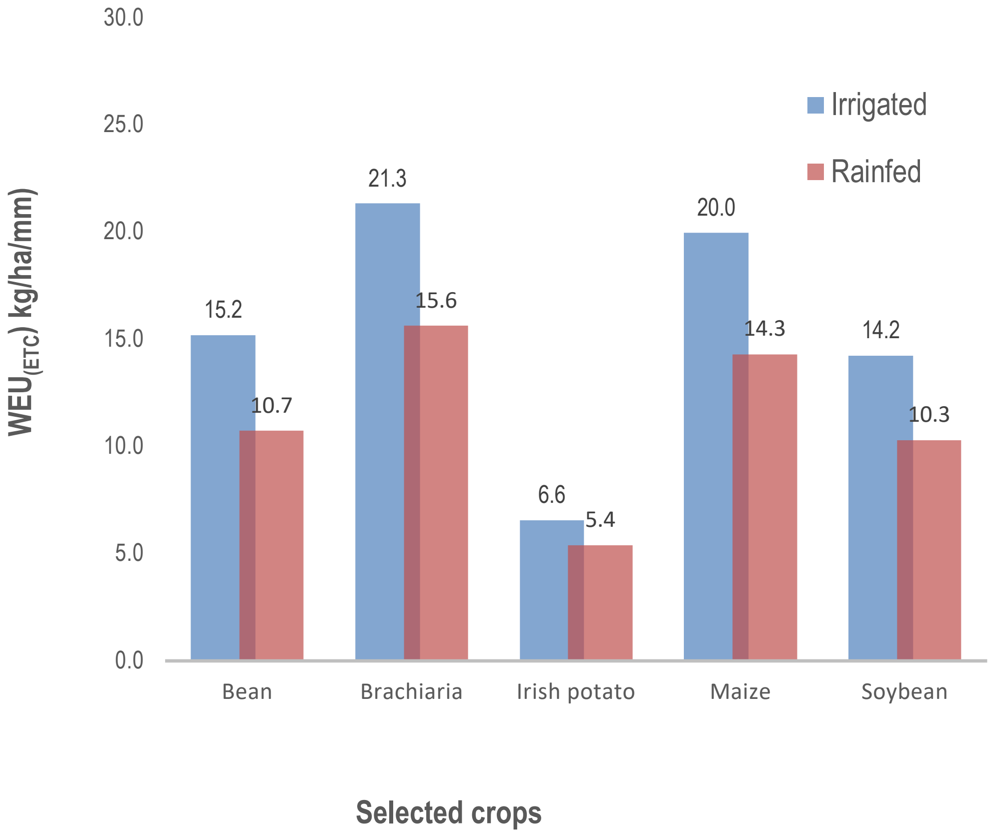

Figure 7: Average WUE based on the actual evapotranspiration (ETc) during the growing season1 and 2

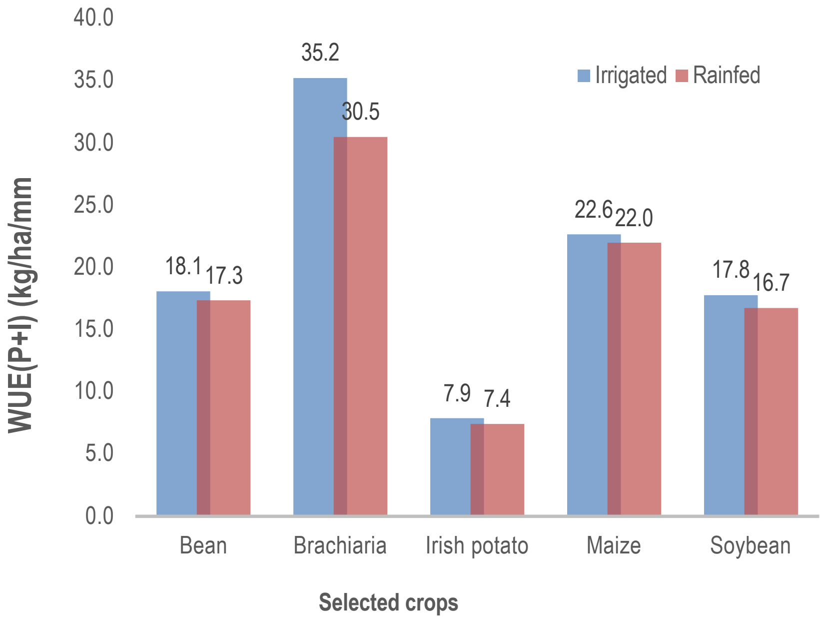

Figure 8: Average WUE based on the total water input (p+I) during the growing seasons 1 and 2

These findings emphasize the importance of precision irrigation to bridge the gap between total water applied and actual crop needs to maximize efficiency in agricultural systems. The results of the two-way ANOVA indicate that WUE is significantly influenced by both the specific crop type and the water management system (irrigated vs. rainfed). To identify these significant differences among treatment combinations, Tukey-adjusted p-values were utilized for pairwise comparisons. These comparisons confirmed numerous significant interactions at $p < 0.05$, particularly highlighting how irrigated crops consistently outperformed their rainfed counterparts in efficiency across both WUE $_{(ETc)}$ and WUE $_{(P+I)}$ metrics. For instance, significant differences were observed between irrigated and rainfed Maize ($p < 0.0001$) and irrigated versus rainfed Beans ($p = 0.0004$) regarding WUE (ETc), reinforcing the finding that supplemental irrigation optimizes physiological performance during critical growth stages.

The results of this study demonstrate that WUE in the region is a dynamic parameter heavily influenced by crop physiology and water management strategies. The observed superiority of irrigated systems over rainfed ones aligns with regional findings that erratic rainfall and intra-seasonal dry spells are the primary limiters of productivity in East and Southern Africa as reported by Omay *et al.* [21].

This stabilization suggests that supplemental irrigation optimizes physiological performance by preventing the stomatal closure and reduced photosynthesis that occur during the frequent dry spells typical of the regional climate as documented by

Harisha *et al*. [14]. Regional research in Zambia confirms that when water becomes limited during critical development stages, such as flowering, yield differences are often wholly due to the plant's ability to maintain a favorable water status as reported by Hamududu and Ngoma [22]

The high efficiency of Brachiaria in this study is consistent with its performance in validation trials in Kenya, where it outperformed traditional grasses like Rhodes grass as reported by Sokupa *et al.* [23]. This superior performance is attributed to its massive root development, which facilitates high nutrients and water uptake even in drought-prone environments. Furthermore, as a climate-smart forage, its ability to produce high foliage biomass under varying moisture levels makes it a resilient option for the region's mixed crop-livestock systems.

This lower WUE of legumes is physiologically linked to the shallow root system of the potato, which makes it one of the most drought-sensitive species in the region as documented by Gervais *et al*. [24]. Drought induces strong perturbations in potato photosynthesis and tuber bulking, often leading to severe yield failures if moisture is not maintained at field capacity.

The data shows a distinct discrepancy between WUE based on total water (P+I) and WUE based on ETc For instance, Season 1 irrigated Beans showed an ETc-based WUE of 20.4 kg /ha/mm DMY versus 18.5 kg/ha/mm of DMY for P+I. Regional studies emphasize that effective use of water is the ability of a crop to maximize soil moisture capture for transpiration while minimizing soil evaporation is a more critical target for yield improvement than WUE alone.

The necessity of bridging this gap through precision irrigation is echoed by findings in Southern Africa, where it has been noted that the advantage of transpiration-based efficiency is that it avoids the compounding effects of soil evaporation and weed-related water loss, Consequently, management practices that synchronize water application with actual crop demand are essential to maximize resource use efficiency in the water-scarce environments of Rwanda and the broader region.

CONCLUSION AND RECOMMENDATIONS FOR DEVELOPMENT

This study demonstrates that drip irrigation management significantly enhances dry matter yield (DMY) and water use efficiency (WUE) across Irish potato, maize, soybean, common bean, and Brachiaria grass in Rwanda's semi-arid regions, Experimental results indicate that maize exhibited the strongest yield response to irrigation, achieving up to 58.2% improvement in Season 1, while Brachiaria grass demonstrated the highest overall WUE at 35.2 kg/ha/mm of DMY, underscoring its physiological resilience. Conversely, Irish potato was identified as the most drought-sensitive species, consistently recording the lowest efficiency metrics due to its shallow root system, Mechanistically, the precision of drip irrigation optimized crop performance by stabilizing soil moisture near field capacity, which prevented plants from reaching their permanent wilting point and sustained the stomatal conductance and CO2 exchange necessary for photosynthesis, These findings confirm that adopting precision irrigation is a critical strategy for mitigating climatic variability and supports Rwanda's strategic goals for sustainable food security and agricultural intensification, as outlined in PSTA 4 and Vision 2050.

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Authors' contributions

Valens Nkundabashaka, the main author of this paper. The co-authors contributed in the Design of research goals, design of methodologies , Acquisition of the financial support for the project, Conducting the research and investigation process, specifically performing the experiments or data/evidence collection, laboratory samples, Application of statistical, mathematical, computational and other formal techniques to analyze study data, data visualization/graphical representation, Management and coordination responsibility for the research activity planning and execution. The authors worked as team upon the completion of the paper.

Conflict of interest

None

Abbreviations

DMY: Dry matter yield
WUE: Water-use Efficiency
WUE(ETc): Water-use Efficiency based on actual crop evapotranspiration
WUE(P+I): Water-use Efficiency based on total water input (precipitation and irrigation)
ETc: Crop evapotranspiration
ETo: Reference evapotranspiration
Kc: Crop coefficient
TAW: Total available water
RAW: Readily available water
SWDi: Soil water depletion
θFC (or FC): Field capacity
θWP (or WP): Wilting point

Zr: Rooting depth
Ks: Water stress coefficient
Dr: Root zone depletion
PSTA 4: Strategic Plan for Agriculture Transformation
MINAGRI: Ministry of Agriculture and Animal Resources
NISR: National Institute of Statistics of Rwanda
CIP: This abbreviation refers to both the Crop Intensification Program and the International Potato Center

Table 1: Soil Physical and Chemical Properties Across Depths at the Experimental Site

Depth (cm)		Sand (%)	Silt (%)	Clay (%)	BD (g/cm³)	FC (%)	WP (%)	pH	TN (%)	SOC (%)	P (%)	K (%)
0-20		64.0	21.0	15.0	1.3	23.0	11.0	4.7	0.1	1.7	0.01	0.1
20-40		66.0	20.0	14.0	1.4	22.9	11.0	4.6	0.1	1.7	0.01	0.1
40-60		67.0	19.0	14.0	1.4	23.1	10.9	4.5	0.1	1.7	0.01	0.1
60-80		64.0	28.0	8.0	1.5	23.0	11.1	4.7	0.1	1.6	0.01	0.1
80-100		68.0	25.0	7.0	1.5	22.9	10.9	4.4	0.1	1.7	0.0198	0.1

Table 2: Fertilizer Application Rates and Nutrient Contributions

Crop	DAP (kg/ha)	KCL (kg/ha)	UREA (kg/ha)	NPK (kg/ha)	Total N (kg/ha)	Total P (kg/ha)	Total K (kg/ha)
Bean	100	30	100	50	72.5	23.8	22.0
Brachiaria Grass	100	100	100	75	76.8	25.6	60.3
Irish Potato	150	125	100	300	124.0	52.3	104.6
Maize	100	75	100	50	72.5	23.8	44.4
Soybean	100	30	100	50	72.5	23.8	22.0

Table 3: Average daily climatic data for season 1 (23rd September 2024 to 31st January 2025)

Variable	Units	Mean	Min	Max
Tmin	°C	13.9	9.0	17.0
Tmax	°C	23.5	18.0	29.0
Mean Relative Humidity	%	78.7	57.5	93.5
Solar radiation	$MJ\ m^{-2}\ day^{-1}$	16.6	9.4	27.8
Wind speed at 2 m	$m\ s^{-1}$	2.4	0.3	7.8
ETo	$mm\ day^{-1}$	3.3	2.1	5.0

Table 4: Average daily climatic data for season 2 (15th February 2025 to 25th July 2025)

Variable	Units	Mean	Min	Max
Tmin	°C	13.7	9.0	22.0
Tmax	°C	22.2	15.0	28.0
Mean Relative Humidity	%	79.7	5.0	98.5
Solar radiation	MJ m^{-2} day^{-1}	18.0	10.2	23.6
Wind speed at 2 m	m s^{-1}	3.0	0.0	7.8
Reference ETo	mm day^{-1}	3.4	1.9	6.4

Table 5: Water balance for season 1

Crop		SWDi (mm)	P (mm)	I (mm)	P + I (mm)	ETc adj (mm)	I (%)	P (%)
Bean		-0.1	197.7	80	277.7	277.8	28.8	71.2
Brachiaria grass		-0.4	256.3	40	296.3	296.7	13.5	86.5
Irish Potato		+0.3	191.4	60	251.4	251.1	23.9	76.1
Maize		+0.9	203.9	100	303.9	303	32.9	67.1
Soybean		+0.5	216.7	80	296.7	296.2	27	73

Table 6: Water balance for season 2

Crop	SWDi (mm)	P (mm)	I (mm)	P + I (mm)	ETc adj (mm)	I (%)	P (%)
Bean	+345.5	584	20	604	258.5	3.3	96.7
Brachiaria grass	+328	533	20	553	225	3.6	96.4
Irish Potato	+166.5	366	60	426	259.5	14.1	85.9
Maize	+362.5	583	80	663	300.5	12.1	87.9
Soybean	+343.5	584	40	624	280.5	6.4	93.6

Table 7: Irrigation performance on Dry matter yield for season 1

Crop	Treatment	DMY (kg/ha)	Increment DMY (kg/ha)	Increment (%)
Bean	Irrigated	4930.7	1640.6	49.90%
Bean	Rainfed	3290.1		
Brachiaria	Irrigated	5851.8	983	20.20%
Brachiaria	Rainfed	4868.8		
Irish potato	Irrigated	1840.9	603.2	48.70%
Irish potato	Rainfed	1237.7		
Maize	Irrigated	8333.5	3065	58.20%
Maize	Rainfed	5268.5		
Soybean	Irrigated	4851.2	1115	29.90%
Soybean	Rainfed	3736.2		

Table 8: Irrigation performance on Dry matter yield for season 2

Crop	Treatment	DMY (kg/ha)	Increment DMY (kg/ha)	increment (%)
Bean	Irrigated	4810.7	722	17.70%
Bean	Rainfed	4088.7		
Brachiaria	Irrigated	7571.1	2476.3	48.60%
Brachiaria	Rainfed	5094.8		
Irish potato	Irrigated	1746	349.3	25.01%
Irish potato	Rainfed	1396.7		
Maize	Irrigated	8071.7	1975.3	32.40%
Maize	Rainfed	6096.4		
Soybean	Irrigated	5091.9	939.4	22.70%
Soybean	Rainfed	4152.5		

REFERENCES

1. **Joselyne M I, Mukamanzi F, Clotilde U, De Dieu B J, Eric H and S J Omar** Optimal Soil Type and Water Need Efficiency for Planning Smart Irrigation in Bugesera, Rwanda's Semi-Arid Region. *Univers J Agric Res.* 2024;12(2):347–55. https://doi:10.3390/w16131842

2. **NISR.** Labor force Survey Quarter 1, 2025. 2025; 1–46.

3. **Niu Y, Wang L, Luo Z, Fudjoe SK, Palta J A and L Li** Effects of Irrigation Practices on Potato Yield and Water Productivity: A Global Meta-Analysis. *Agronomy*. 2025;15(8):1–18. https://doi:10.3390/agronomy15081942

4. **Drastig K, Singh R, Telesca FM, Carra SZ and J Jordan** A Review of Nutritional Water Productivity (NWP) in Agriculture: Why It Is Promoted and How It Is Assessed? *Water* (Switzerland). 2023; **15(24):** 1–24. https://doi:10.3390/w15244278

5. **Islam MM, Alharthi M, Alkadi RS, Islam R, and AKM Masum** TabNet for crop yield prediction: promoting sustainability and climate resilience in Saudi Arabian agriculture. *Cogent Food and Agriculture.* 2025; **11(1).** https://doi.org/10.1080/23311932.2025.2529369

6. **Torino AB, do Nascimento Júnior LF, de Brito MF, Lima J D P, Gonçalves WG and C Eduardo** Agronomic performance of maize and Brachiaria grasses cultivated at monocropping and intercropping in a compacted Latossolo. *Aust J Crop Sci.* 2020; **14(9):** 1533–40. https://doi.org/10.21475/ajcs.20.14.09.p2773

7. **Schmidt N and J Zinkernagel** Crop Coefficients and Irrigation Demand in Response to Climate-Change-Induced Alterations in Phenology and Growing Season of Vegetable Crops. *Climate*. 2024; **12(10).** https://doi:10.3390/cli12100161

8. **Zhang L, Bai G, Evett SR, Colaizzi PD, Xue Q and G Marek** Increased irrigation could mitigate future warming-induced maize yield losses in the Ogallala Aquifer. 2025;1–9.

9. **Alharbi S, Felemban A, Abdelrahim A and M Al-Dakhil** Agricultural and Technology-Based Strategies to Improve Water-Use Efficiency in Arid and Semiarid Areas. *Water* (Switzerland). 2024; **16(13).** https://doi:10.3390/w16131842

10. **Bohra S and Jani CK** Comparative Study of Photosynthetic Efficiency in C3 vs C4 Plants Under Climate Stress. 2025; **4(2).**

11. **Dwivedi AK, Upreti H and CSP Ojha** Wheat Yield Modelling using InfoCrop and DSSAT Crop Simulation Models. *Indian Journal of Agricultural Research.* 2022; **56(6):** 646–52. https://doi:10.18805/IJARe.A-5981

12. **Hussein MA, Riga FT, Derseh MB, Assefa TT, Worqlul AW and A Haileslassie** Application of Irrigation Management and Water-Lifting Technologies to Enhance Fodder Productivity in Smallholder Farming Communities: A Case Study in Robit Bata, Ethiopia. *Agronomy*. 2024; **14(5).** https://doi:10.3390/agronomy14051064

13. **Kelley B, Dong Y, Chilvers M I and N Das** Understanding the impact of irrigation scheduling on water-use efficiency in corn and soybean production in humid climates: insights from on-farm demonstration. 2025;(May):1–15. https://doi:10.3389/fagro.2025.1496198

14. **Harisha CB, Rane J, Halagunde Gowda GR, Chavan SB, Chaudhary A and AK Verma** Effect of Deficit Irrigation and Intercrop Competition on Productivity, Water Use Efficiency and Oil Quality of Chia in Semi-Arid Regions. *Horticulturae*. 2024; **10(1).** https://doi:10.3390/horticulturae10010101

15. **Alkaff M, Basuhail A and Y Sari** Optimizing Water Use in Maize Irrigation with Reinforcement Learning. *Mathematics*. 2025; **13(4)**. https://doi:10.3390/math13040595

16. **Twahirwa A, Oludhe C, Omondi P, Rwanyiziri G and JS Ndakize** Assessing Variability and Trends of Rainfall and Temperature for the District of Musanze in Rwanda. 2023.

17. **Zeitoun R, Vandergeest M, Vasava HB, Vitor P, Machado F and G Parkin** In-Situ Estimation of Soil Water Retention Curve in Silt Loam and Loamy Sand Soils at Different Soil Depths. 2021.

18. **Saxton KE and PH Willey** The Spaw Model for Agricultural Field and Simulation. 2009;1–36.

19. **Allen RG and M SMITH** FAO Irrigation and Drainage Paper Crop by. Irrigation and Drainage. 1998; **300(56):** 300.

20. **Magruder J and C Ndahimana** Impacts, maintenance and sustainability of irrigation in Rwanda. 2020;(March).

21. **Omay PO, Muthama NJ, Oludhe C, Kinama JM, Artan G and Z Atheru** Changes and variability in rainfall onset, cessation, and length of rainy season in the IGAD region of Eastern Africa. *Theor Appl Climatol*. 2023; **152(1–2):** 871–93. https://doi:10.1007/s00704-023-04433-0

22. **Hamududu BH and H Ngoma** Impacts of climate change on water resources availability in Zambia: implications for irrigation development. *Environment, Development and Sustainability.* 2020; **22(4):** 2817–38. https://doi:10.1007/s10668-019-00320-9

23. **Sokupa MI, Mupangwa JF, Washaya S, Tikwayo SE and K Mopipi** The nutritive value of Panicum maximum and Brachiaria brizantha grass species. Acta Agriculture Scandinavica A: *Animal Sciences.* 2024; **73(1–2):** 1–9. https://doi:10.1080/09064702.2023.2249903

24. **Gervais T, Creelman A, Li XQ, Bizimungu B, De Koeyer D and K Dahal** Potato Response to Drought Stress: Physiological and Growth Basis. *Front Plant Sci.* 2021;12(August): 1–10. https://doi.org/10.3389/fpls.2021.698060