Effect of Varying Irrigation Levels on Growth and Yield of Serengeti and Theresa French Bean Cultivars: A Case Study in Huye District, Rwanda

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Abstract

Effective irrigation management is essential for maximizing crop yield and quality while conserving water resources. This study evaluated the impact of varying irrigation levels on the growth and yield of two French bean cultivars, Serengeti and Theresa, conducted in 2024 at the Agricultural Research Center of Rwanda Polytechnic – Huye College. Key objectives included determining crop water requirements, establishing irrigation schedules based on daily soil water balance, and examining the effects of three irrigation regimes (Full irrigation (100% ETc) , Deficit irrigation(50% ETc), and Rainfed as Control on yield parameters across both cultivars. The experiment followed a split-plot design in a Randomized Complete Block Design with three replications. Soil moisture levels were monitored using PR2- Moisture Sensors. The results of conducted field experiments revealed that, the seasonal irrigation water requirements for full irrigation, deficit irrigation, and rainfed treatments were 111.38 mm, 99.5 mm, and 24.5 mm, respectively. Seasonal evapotranspiration rates were measured at 160.4 mm for full irrigation, 143.9 mm for deficit, and 80.84 mm for rainfed. The fresh pod yield ranged between 5.9 – 11.7 tons ha^{-1} for Serengeti and 5.3 – 20.3 tons ha^{-1} for Theressa, while dry matter yields varied from 1.0 – 1.66 tons ha^{-1} for Serengeti and 0.8 – 2.88 tons ha^{-1} for Theressa. Plant height ranged from 22 cm to 40.1 cm, and pod lengths for Serengeti and Theressa were between 9.3 – 17.64 cm and 8.8 – 15.8 cm, respectively. The mean number of grains per pod was 7. Yield response factors (ky) for Serengeti and Theressa were 1.029 and 1.20, respectively. The highest crop evapotranspiration productivity (WPET) and water productivity (WP-irrigation) were recorded for Theressa at 127.2 kg $ha^{-1}mm^{-1}$ and 135.6 kg $ha^{-1}mm^{-1}$, respectively. Monitoring soil moisture balance highlights the economic advantages of efficient irrigation techniques tailored to local conditions.

Keywords: French bean, Serengeti, Theresa, Irrigation levels, Moisture sensor

1. Introduction

The French bean (*Phaseolus vulgaris*) is a widely produced and consumed legume in sub-Saharan Africa, particularly among smallholder farmers (Raatz et al., 2019). It is a nutritious vegetable that can be grown in various soil types but does not tolerate waterlogging (Singh & Chauhan, 2009). French beans are a primary legume for direct human consumption, containing high water content and being rich in proteins, vitamins, minerals, and dietary fiber, without cholesterol (Chaurasia, 2020; Larochelle et al., 2016).

In Rwanda, beans are the second-most popular crop after bananas, with 88 percent of farmers cultivating them (NISR, 2021). Beans occupy 20.4 percent of the cultivatable land area, with a mean annual production of around 450,000 metric tons (NISR, 2017). In 2023, approximately 53,592 kg of French beans were exported, generating $184,267 in revenue (NAEB, 2023). Beans supply 32 percent of caloric intake and 65 percent of protein intake in Rwandan household diets (Onyango, 2021). However, French bean production remains limited due to reliance on rain-fed agriculture, leading to dependency on unreliable weather conditions (Uwanyirigira et al., 2023).

Moreover, accurately estimating crop water requirements (ETc) is essential for irrigation scheduling and water management (Mehta & Pandey, 2016). Irrigation scheduling, based on crop water requirements and available weather data, has been recommended by various researchers, including Doorenbos & Pruitt (1975), Blaney & Criddle (1950), Turc (1961), Christiansen (1968), Priestly & Taylor (1972), Hargreaves & Samani (1985), and Allen et al. (1998). The Checkbook Approach was suggested, and soil water content measurement tools, such as gypsum blocks (Werner, 2002) and Delta-T moisture meters with PR2 Profile Probe sensors (Delta-T Devices Ltd, 2013), are commonly used.

This study aims to optimize irrigation practices as an alternative strategy for the Serengeti and Theressa French bean varieties, which are adapted to local conditions and widely available in the market, to balance water-use efficiency with crop production. French beans (*Phaseolus vulgaris*) are selected as a model crop due to their popularity for their tender pods and nutritional value within the community. Improving irrigation practices for French beans not only enhances agricultural productivity and food security but also promotes sustainable water management, contributing to environmental conservation and resilience against climate variability.

2. Material and Methods

A field experimental study was conducted at Rwanda Polytechnic (RP) -Huye College’s Agricultural research center, located at 2°36'37''S, 29°43'59''E. RP Huye College is in the Huye District of Rwanda’s Southern Province, at an elevation of 1700 meters (DDS, 2018) and an average temperature of 20°C with an annual rainfall of 1160 mm. Approximately 97% of agriculture in Huye District is traditional, though there is a trend toward modern agriculture to enhance production (NISR, 2015).

The experiment examined the Serengeti variety, which produces long, thick, dark green pods and black seeds with moderate resistance to common diseases, and the Theresa variety, known for its deep green pods and white seeds. Both varieties mature early, around 55–65 days for Serengeti and 55–60 days for Theresa. The bean seeds were planted with row spacing of 40 cm and 10 cm between plants.

The drip irrigation system used a tank elevated 3 meters above the ground, with water delivered by gravity through a mainline of 32 mm in diameter connected to two submain lines of 25 mm diameter, each controlled by a water valve. A total of 42 driplines with 2 Lh^{-1} emitters irrigated the treatment plots, which covered 96.6 m². Treatment plots measured 4.6 m x 2.5 m and were spaced 0.6 m apart for easy data collection.

The soil texture class is sandy loam, identified using the Soil Texture Decision Chart method (Soil Survey Staff, 1999). The soil organic carbon (OC) levels were 1.9% and 1.4% at depths of 0–30 cm and 30–60 cm, respectively, with an average of 1.6%. Organic matter (OM) content was calculated at 2.8% by converting OC using a multiplication factor of 1.724 (Magdoff and Van Es, 2021). The field capacity (FC) and permanent wilting point (PWP) were 22.2% and 14.05%. The average water content at saturation was 43.3%, and the saturated hydraulic conductivity was 22.0 mm hr^{-1} (Table 1).

Table 1. Soil properties of experimental treatment

Parameters*	Units	Soil layer		
	cm	0-30	30-60	0-60
sand	%	74	70	72
Silt	%	7	9	8
clay	%	19	21	20
Texture	Class	SaL	SaCL	SaL
Bulk density	g/cm^3	1.48	1.52	1.5
FC	% v	21.8	22.6	22.2
PWP	% v	13.8	14.3	14.05
TAW	mm	24	24.9	48.9
Sat.	% v	44.1	42.6	43.3
Sat.hydr.cond	mm/h	25.7	18.8	22
OC	%	1.9	1.4	1.6
OM	%	3.2	2.4	2.8

*TAW for total depth of 60cm is the summation of two-soil layers depth. SaL: sandy loam, SaCL: sand clay loam, OM: Organic matter, OC: Organic carbon, Sat.Hydro.Cond.: Saturated hydraulic conductivity, Sat: Saturation.

2.1. Experimental Design of the study

A split plot experiment in a Randomized Complete Block Design (RBD) was used in the study. Irrigation levels were assigned as main plots, while French bean varieties served as subplots, with three replications and detailed in (Table 2) and (

Figure **1**). The treatments included three irrigation levels, determined by soil water deficit (SWD) management, which was monitored using a PR2 profile soil moisture sensor. Irrigation depths were set to refill up to the water stress-free level (Ks = 1). To ensure good crop establishment, no stress was allowed during the emergence phase. All treatments were irrigated up to field capacity before starting the irrigation management phase. A daily soil water balance spreadsheet managed in Excel was used to monitor irrigation scheduling.

Table 2. Arrangement of Experimental Design

Treatments	**Description of treatments**
I_{100} V_1	French beans of the *Serengeti* variety, with full irrigation water applied at 100% of evapotranspiration, experienced no water stress, as the water deficit was consistently maintained at Ks = 1

I_{100} V_2	French beans of the *Theresa* variety, with full irrigation water applied at 100% of evapotranspiration, experienced no water stress, as the water deficit was consistently maintained at Ks = 1
I_{50} V_1	*Serengeti* variety was subjected to deficit irrigation, with a water stress factor of less than 1 (Ks < 1) until Ks reached 0.5. Irrigation water was supplied when the water stress factor was around Ks = 0.5. At this point, evapotranspiration did not reach the potential evapotranspiration.
I_{50} V_2	*Theresa* variety was subjected to deficit irrigation, with a water stress factor of less than 1 (Ks < 1) until Ks reached 0.5. Irrigation water was supplied when the water stress factor was around Ks = 0.5. At this point, evapotranspiration did not reach the potential evapotranspiration.
Control	Rain-fed without irrigation (control). However, it received the same amount of water during the emergence period.

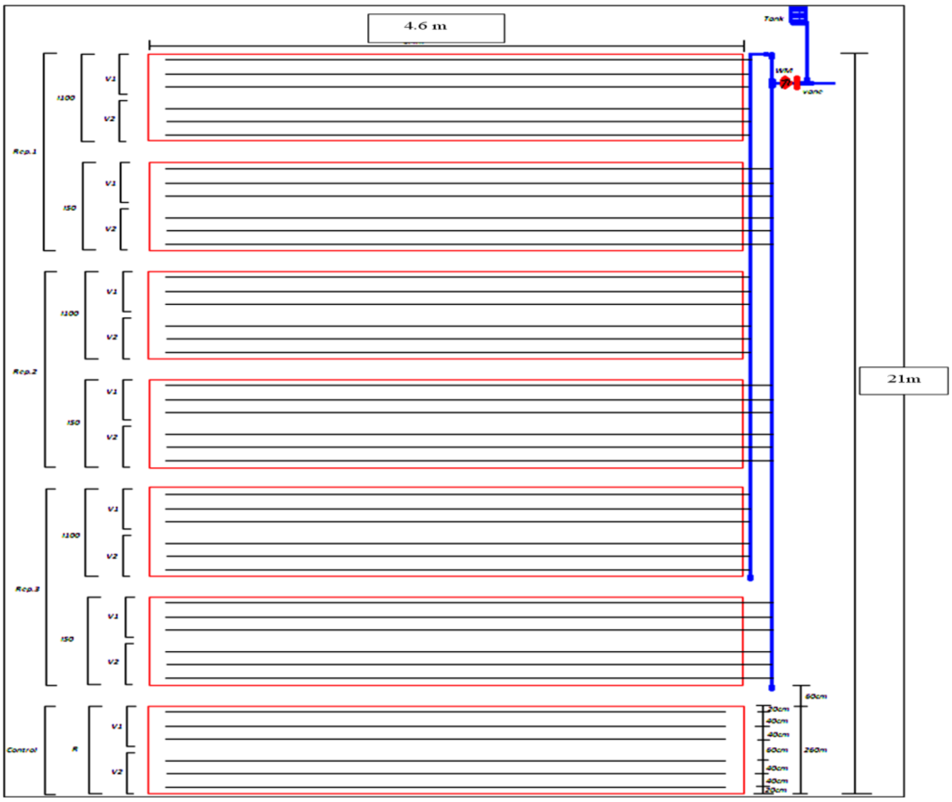


Figure 1. Layout of Experimental Treatments

Estimation of irrigation water requirement

A spreadsheet for the daily soil water balance (SWB) approach was used to quantify the amount of net irrigation water requirement for each treatment (I amount), expressed in liters, using Equation 1 (Ertek & Kara, 2013). The seasonal irrigation water requirement was determined as the summation of the net irrigation requirement for each irrigation event. To track irrigation scheduling, the water deficit was estimated using Equation 2 (Andales et al., 2015; Allen et al., 1998).

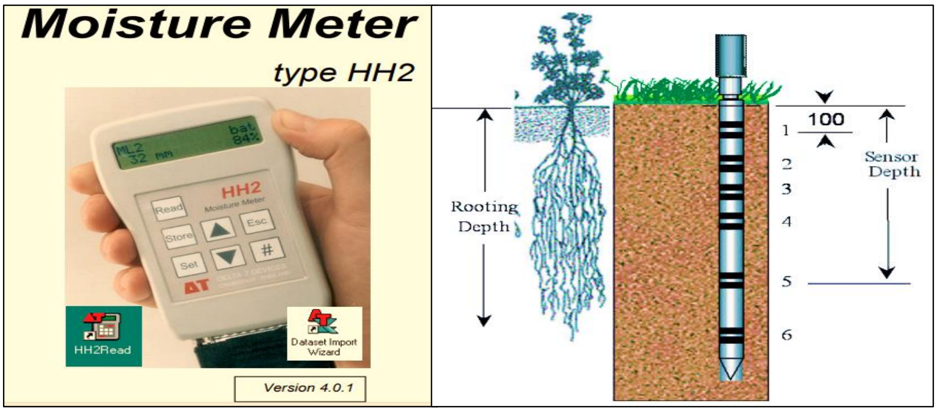
$$I_{amount} = D_c \text{ x } A \qquad (1)$$

$$D_c = D_p + ET_C - P - I - U + SRO + DP \qquad (2)$$

Where *Dc* is the soil water deficit in the root zone on the current day (mm). If Dc was negative, it is set to 0.0 as the full level of field capacity; *Dp* is the soil water deficit on the previous day (mm); *ETc* is the crop evapotranspiration rate for the current day (mm); *P* is the gross precipitation for the current day (mm); *I* is the net irrigation amount infiltrated into the soil for the current day; *U* is the upflux of shallow groundwater into the root zone, which is below 1 m depth, (mm); *SRO* is surface runoff (mm); and *DP* is deep percolation or drainage (mm). However, it is difficult to estimate *U*, *SRO*, and *DP* in the field; therefore, these variables are neglected.

Soil moisture content

To estimate the current moisture content, a Delta-T moisture meter with PR2 Profile Probe sensors was used(Figure 2). The soil moisture deficit was recorded in an Excel sheet using an HH2 connector (Delta-T Devices Ltd, 2013).



Photos credited by Delta-T Devices Ltd, 2013.

Figure 2. Moisture Meter type HH2 at left side and Profile Probe Sensor at right side

Crop evapotranspiration

Estimating Crop evapotranspiration (ETc) in mm per day was termined by using Equation 3 and 4 from FAO-56 (Allen et al., 1998). *Ks* was estimated using methods from Andales et al. (2015) and Allen et al. (1998).

$$ET_c = K_s \text{ x } K_c \text{ x } ET_o \quad (3)$$

$$K_s = \frac{TAW - D}{(1 - MAD) \text{x } TAW} \quad (4)$$

Where *ETo* is the evapotranspiration rate (mm/day) from a reference crop; *Kc* is a crop coefficient that varies by crop development stage, and *Ks* is a water stress coefficient, *TAW* is total available water in the soil root zone (mm); *D* is defined as water shortage relative to field capacity, mm; *MAD* is management allowed depletion (%).

Determination of yields and yields parameters

Pod yield production was evaluated by selecting ten French bean plants from a 1m² area in each treatment plot. Marketable and non-marketable green pods were weighed in kilograms using a precision balance. Total yield per hectare was calculated by multiplying the total area of each plot. Dry matter yield was determined by drying ten green pods from each plot at 70°C for 48 hours, with total dry weight expressed in tons per hectare. Plant height was measured at harvest from the base to the tip on ten randomly selected plants per plot using a tape measure. Pod lengths were assessed by measuring ten pods from each plot. The number of pods per plant was counted during harvest, and ten plants were sampled to count grains per pod. Nodes per plant were also recorded by counting the total nodes on the main stem and dividing by two.

Determination of yields moisture relationship

The yield response factor (Ky) was applied in Equation 5 following the Stewart model (1976), as well as the works of Doorenbos and Kassam (1979) & Hakiruwizera et al. (2023). Water productivity for irrigated treatment and crop evapotranspiration were assessed using Equations 6 and 7 (Pereira et al., 2020; Ertek et al., 2007; Hakiruwizera et al., 2023).

$$[1-(Y_a/Y_m)] = k_y[1-(ET_a/ET_m)] \quad (5)$$

$$WP_{irrig} = \frac{Y - Y_{rain}}{IWU} \quad (6)$$

$$WP_{ET} = \frac{Y_a}{ET_{act}} \quad (7)$$

Where: *Ky* is the yield response factor; *Ya* is the actual total fresh yield (kg ha^{-1}); *Ym* is the maximum total fresh yield (kg ha^{-1}); *ETa* is the actual water consumption (mm); *ETm* is the maximum water consumption (mm); *IWU* is irrigation water use; ET_{c_act} is the actual consumptive use; *Y* is the total fresh yield (kg ha^{-1}); Y_{rain} is the total fresh yield obtained under rainfed conditions (kg ha^{-1}); WP_{irrig} is the water productivity for irrigated treatment; and WP_{ET} is the water productivity for crop evapotranspiration.

2.2. Statistical analysis

The mean square of the interaction between irrigation levels and varieties was used as the error term to test the interaction between both factors. The least significant difference (LSD) at $p = 0.05$ from Fisher's test was used to identify statistically significant differences between treatment means in the ANOVA. All analyses were performed using the MINITAB 17 software (© 2013 Minitab Inc., Language Pack in English version 17.1.0.0). Linear regression analyses were conducted to examine the relationship between yields and evapotranspiration, irrigation water applied, and the best relationship between yield and water productivity using Microsoft Excel 2010.

3. Results and Discussion

3.1. Irrigation water requirement, moisture content depletion depletion and Crop water requirement

Figure 3 indicates that the irrigation water requirements (I_{amount}), Effective rain fall (Eff.rainfall), reference evapotranspiration (ETo), Seasonal Crop Water Consumption(ETc), and soil moisture depletion(D_c) in I_{100} V_1 and $I_{100}V_2$ (French bean varieties *Serengeti* and *Theressa*) were determined using full irrigation at 100% evapotranspiration (ETc). Seasonal irrigation water requirements totaled 111.38 mm, with the highest daily demand of 11 mm on July 17, 2024. The total effective rainfall during the experiment was 33 mm, recorded over eight events, with a maximum of 11 mm on May 3, 2024. Irrigation needs increased over time, following the crop's growth stages. Daily reference evapotranspiration (ETo) was measured cumulatively at 200 mm per season. Both ETc and adjusted ETc were recorded at 160.4 mm per season, as the water stress coefficient (Ks) was 1, indicating no water stress. Crop evapotranspiration (ETc) aligned with studies by as Laishram et al. (2023), Chandra et al. (2023) and Mizero (2018). Irrigation was scheduled to maintain soil moisture near field capacity, especially during the initial and development stages. At maturity, irrigation was applied below field capacity but above readily available water (RAW) to prevent stress-induced yield loss.

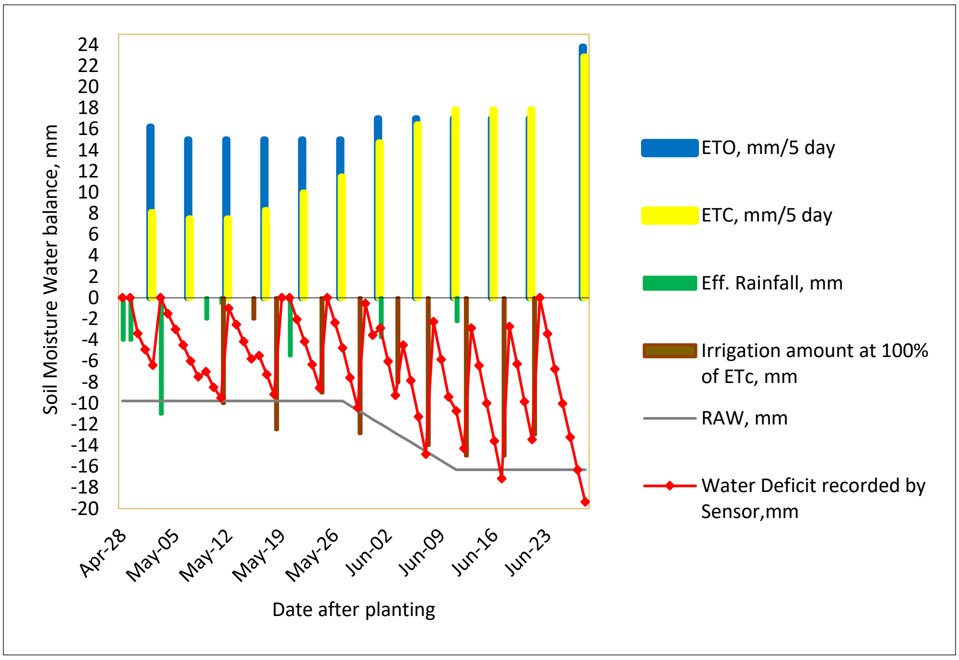


Figure 3. Soil moisture balance for full irrigation at 100% of ETc, Ks=1

Figure 4 indicates that for $I_{50}V_1$ and $I_{50}V_2$, irrigation was applied at 50% of ETc. Effective rainfall totaled 33 mm, with a seasonal irrigation requirement of 99.5 mm and a peak daily application of 20 mm to restore field capacity. Irrigation needs rose from development to maturity, with the beans requiring 62 days to harvest. Here, Ks was maintained at 0.5, indicating mild water stress as ETc did not meet its potential. Actual ETc was recorded at 143.9 mm per seasonal. Allen et al. (1998) described that during limited water availability, Ks values below 1 restrict ETc.

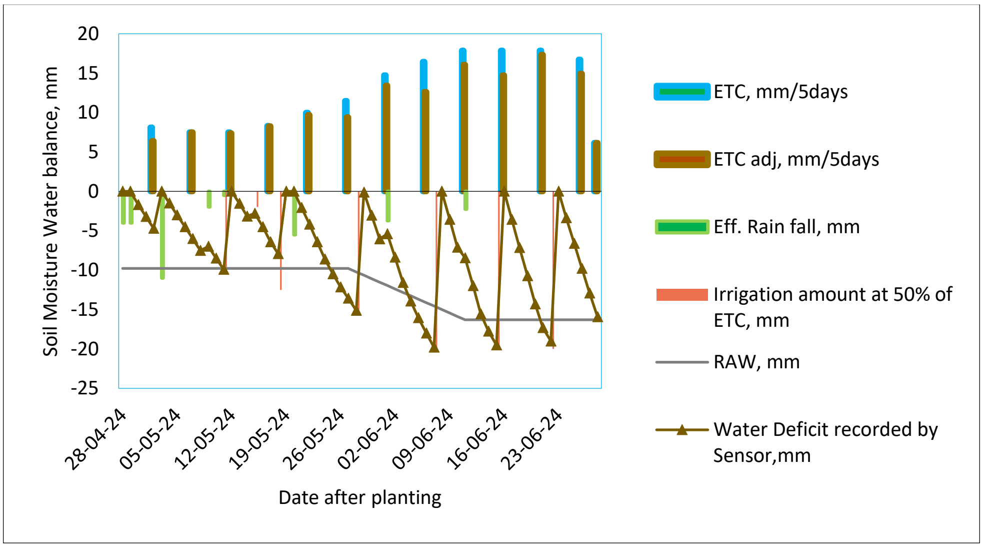


Figure 4. Soil moisture balance for deficit irrigation at 50% of ETc (Ks=0.5)

Figure 5 indicates that under rainfed conditions starting May 18, 2024, French beans received water from rainfall only, except for initial root establishment. Field capacity was considered the zero line on the y-axis, with negative values showing depletion. Below the RAW line, the crop experienced water stress, leading to higher energy use to extract soil moisture. Actual ETc was 80.84 mm per seasonal, with unmet crop water needs.

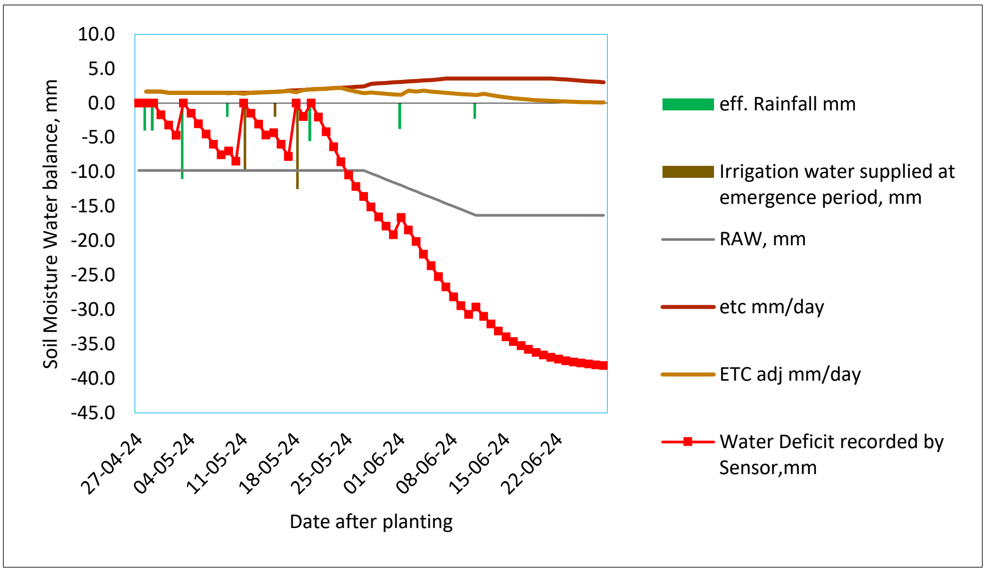


Figure 5. Soil moisture balance for rainfed

3.2. Effect of irrigation water levels and varieties to the yields and yield parameters

Table 3 shows how different irrigation levels and French bean varieties influence various yield and growth parameters, using a statistical analysis approach. The analysis of irrigation levels and French bean varieties on yield and growth parameters reveals clear trends in response to varying water availability and varietal differences. Full irrigation (I_{100}) produced the most robust growth and highest yields across all measured variables, as supported by research demonstrating that optimal irrigation levels significantly enhance yield and dry matter in legumes (Smith et al., 2020; Johnson & Patel, 2019). Under full irrigation, French beans yielded an impressive 16.06 tons per hectare and produced 2.27 tons of dry matter. Plants reached a height of 40.08 cm, with pod heights of 16.72 cm, averaging 19.24 pods per plant, 6.55 grains per pod, and 14.45 nodes per plant. Statistically, these results are highly significant, with a p-value of 0.000 across all parameters. These results are corresponding to findings by Collins et al. (2021), who noted that adequate water access improves pod and grain formation due to enhanced photosynthetic activity and nutrient transport.

Deficit irrigation (I_{50}) reduced yields and growth parameters, but the plants still performed better than those under rainfed conditions. The studies conducted by González & Herrera (2022) showing deficit irrigation can sustain moderate yields while conserving water. The yield dropped to 10.45 tons per hectare, with a dry matter yield of 1.65 tons. Plant height and pod height were also reduced under deficit irrigation, reaching 33.33 cm and 12.82 cm, respectively. Other yield parameters, such as the number of pods per plant (11.84), grains per pod (4.03), and nodes per plant (8.92), were also lower than in fully irrigated plants, consistent with findings by Raza & Choudhury (2022) and also which aligns with findings from Pérez et al. (2020), indicating the significant yield penalty associated with water-stressed conditions in beans. The pattern consistent with research indicating that reduced irrigation leads to shorter plants and fewer pods due to moisture stress (Tan et al., 2018). Even though the water stress under deficit irrigation lowered growth metrics compared to full irrigation, researchers such as Lim et al. (2021) argue that deficit irrigation can be an effective water-saving strategy with moderate impacts on yield.

Rainfed conditions resulted in the lowest yields and poorest growth metrics. Here, French bean yields were only 5.60 tons per hectare, with 0.93 tons of dry matter. The plants under these conditions grew to an average height of 22 cm, with pod heights of just 9.05 cm, findings that align with Gutiérrez et al. (2020). Yield components were also significantly lower, with 7.00 pods per plant, 3.14 grains per pod, and only 2.83 nodes per plant. This treatment was statistically distinct from both full and deficit irrigation, underscoring the considerable impact of limited water availability on growth and yield. Other researchers confirm that rainfed conditions lead to suboptimal growth and yield in legumes due to inadequate water availability, which hampers nutrient uptake and biomass production (Martínez and Singh, 2023; Wang et al., 2019).

Among the two French bean varieties evaluated, Theresa (V_2) generally outperformed Serengeti (V_1). The Theresa variety yielded 12.29 tons per hectare, with a dry matter yield of 1.84 tons, while Serengeti yielded only 9.08 tons per hectare and 1.40 tons of dry matter, consistent with research on varietal differences in legume response to water availability (Baker & Yilmaz, 2020). Although the two varieties showed similar plant heights, Theresa exhibited better yield components, with more pods per plant (14.03) and slightly higher grain numbers per pod (4.68), along with slightly fewer nodes per plant (8.51) than Serengeti, findings similar to studies by Osei et al. (2022). Furthermore, De Silva & Rojas (2021) report that certain varieties exhibit enhanced drought tolerance, which supports the marginally better performance of Theresa under deficit irrigation. Other studies similarly conclude that balancing optimal irrigation with suitable varieties is essential for sustainable and productive legume cropping systems (Santos et al., 2023; Ma & Lin, 2021).

The interaction between irrigation levels and variety further highlighted the advantage of full irrigation. The combination of full irrigation with the Theresa variety (I_{100} x V_2) yielded the highest results across nearly all parameters, producing 20.31 tons per hectare and 2.88 tons of dry matter. Plants in this treatment reached an average height of 40.67 cm, with a pod height of 15.79 cm. This interaction also produced the most pods (21.70 per plant) and nodes (14.70 per plant), underscoring the synergistic effect of full irrigation and the higher-yielding variety. Full irrigation with the Serengeti variety (I_{100} x V_1) was similarly productive, yielding 11.70 tons per hectare and showing competitive values for growth metrics, although slightly below those of Theresa. Related studies that show that optimal water levels combined with resilient varieties lead to synergistic effects on yield (Ahmed et al., 2021). This trend is also observed by Kumar & Fernandez (2020), who reported that growth attributes such as plant height, pod number, and node formation are maximized when high-yielding varieties receive sufficient irrigation.

Table 3. Effects of irrigation leves, varieties and interactions on yields and yields parameters on French bean

Treatments	French bean pod production(Ton ha$^{-1)}$	Dry matter yield(Ton ha$^{-1)}$	Height of plant(cm)	Pod height(cm)	Number of Pods/plant	Number of Grains/pod	Number of Nodes/plant
Main Effect							

I100: Full Irrigation	16.06 A	2.27A	40.08 A	16.72A	19.24A	6.55 A	14.45A
I50: Deficit Irrigation	10.45 B	1.65 B	33.33 B	12.82B	11.84B	4.03 B	8.92 B
Rainfed	5.60 C	0.93 C	22.00 C	9.05 C	7.00 C	3.14 B	2.83 C
P-value	0.000	0.000	0.000	0.000	0.000	0.000	0.000
SubPlots							
V1: Serengetti variety	9.08 B	1.40 B	31.53A	13.30A	11.34 B	4.47 A	8.96 A
V2: Theresa variety	12.29 A	1.84 A	32.08 A	12.43B	14.03A	4.68 A	8.51 A
P-value	0.019	0.022	0.59	0.003	0.006	0.59	0.447
Interactions							
I100 x V1	11.70 B	1.66 B	39.50 A	17.64A	16.77 B	6.54 A	14.20 A
I100 x V2	20.31 A	2.88 A	40.67 A	15.79B	21.70 A	6.57 A	14.70 A
I50 x V1	9.64 BC	1.53BC	32.91 B	12.95C	10.60 CD	3.94 B	10.00B
I50 x V2	11.26 B	1.78 B	33.75 B	12.69C	13.07 C	4.13 B	7.83 C
Rainfed x V1	5.90 C	1.04CD	22.17 C	9.30 D	6.67 E	2.94 B	2.67 D
Rainfed x V2	5.30 C	0.85 D	21.84 C	8.80 D	7.34DE	3.33 B	3.00 D
P-value	0.020	0.017	0.82	0.035	0.12	0.86	0.144
S.E ±	1.29	0.174	1.89	0.778	1.34	0.382	1.18
St.Dev., LSD, P=0.05	5.49	0.738	8.04	3.302	5.67	1.622	5.02
Means that do not share a letter are significantly different at P value <0.05.							

3.3. Yields moisture relationships

Water productivity (WP, kg $ha^{-1}mm^{-1}$) for the Theressa French bean variety was 127.2 kg $ha^{-1}mm^{-1}$ under full irrigation and 65.5 kg $ha^{-1}mm^{-1}$ under rainfed conditions. The irrigation WP for the Theressa variety (135.6 kg $ha^{-1}mm^{-1}$ and 60.0 kg $ha^{-1}mm^{-1}$ in $I_{100}V_2$ and $I_{50}V_2$) surpassed that of the Serengeti variety (52.1 kg ha^{-1} mm^{-1} and 37.6 kg ha^{-1} mm^{-1} in $I_{100}V_1$ and $I_{50}V_1$). Abuarab et al. (2020) found water productivity ranged from 56.55 kg·ha^{-1}·mm^{-1} at 80% ETc to 23.80 kg $ha^{-1}mm^{-1}$ at 60% ETc, while Mizero (2018) reported crop water productivity ranging from 1.6 to 4.2 kgm^{-3}.

Figure 6 illustrates the yield response factor (Ky) for two French bean varieties (Serengeti and Theressa). Ky values of 1.029 (R^2 =0.98) for Serengeti and 1.20 (R^2 =0.99) for Theressa were determined. Abuarab et al. (2020) reported lower Ky values of 0.8453 and 0.856, likely due to climatic variations, crop variety, water management, soil characteristics, and differences in irrigation practices. Stewart's (1976) classification describes Ky values between 1 and 1.15 as moderately high and those above 1.15 as high, which aligns with the findings of Abuarab et al. (2020) who reported Ky values of 1.15 and 1.23.

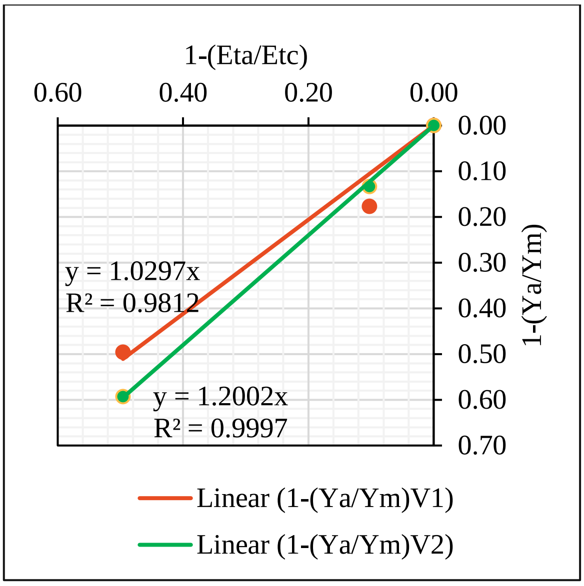


Figure 6. Yield response factor (Ky) for Serengeti(V1) and Theressa (V2) French beans

Figure 7 highlights the polynomial relationship between seasonal evapotranspiration (ET) and fresh pod yield for the Serengeti and Theressa French bean varieties, given by $y = 0.0008\ ETc^2 - 0.1272\ ETc + 10.758$ for Serengeti and $y = 0.0058\ ETc^2 - 1.2037ETc + 64.834$ for Theressa. The results indicate that the yields reduction affected by water deficit is more significant for Theressa than in Serengeti varieties, with higher Ky values in Theressa reflecting its greater sensitivity to water deficits.

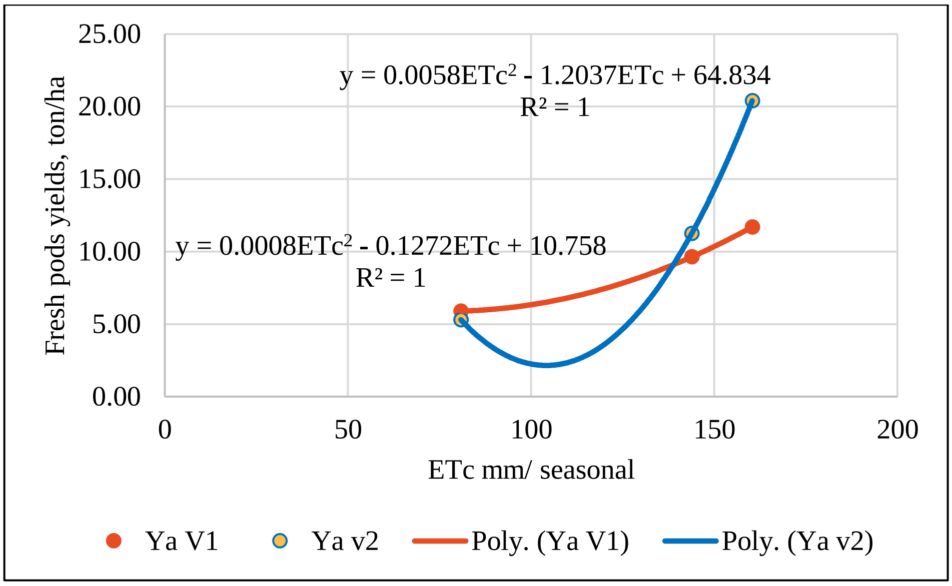


Figure 7. Relationship between Fresh pod yields and crop evaporation

4. Conclusion

This experimental study demonstrated the critical role of effective irrigation management in optimizing growth and yield in French beans. Conducted at the Agricultural Research Center of Rwanda Polytechnic Huye College, it evaluated two cultivars under varying irrigation regimes. Full irrigation resulted in a remarkable fresh pod yield of 20.31 tons ha^{-1} for Theressa and 11.70 tons ha^{-1} for Serengeti, while dry matter yields reached 2.88 tons ha^{-1} and 1.66 tons ha^{-1}, respectively. Deficit irrigation still provided better results, with yields of 10.45 tons ha^{-1} for Theressa, compared to just 5.60 tons ha^{-1} under rainfed conditions. The findings underscore that tailored irrigation practices enhance productivity and water use efficiency, with Theressa exhibiting water productivity of 135.6 kg $ha^{-1}mm^{-1}$ under full irrigation. However, in the regions with limited water resources, deficit irrigation can be adopted to balance the water productivity and yield gap in rainfed conditions.

References

1. Abuarab, M.E., Hafez, S.M., Shahein, M.M., Hassan,A.M., El-Sawy, M.B.I.,. El-Mogy, M.M. & Abdeldaym, E.A. (2020). Irrigation scheduling for green beans grown in clay loam soil under a drip irrigation system. Water SA 46(4), 573–582.
2. Ahmed, M., Liu, Y., Zheng, J., & Zhang, J. (2021). Effects of water management and genotype on growth, yield, and water use efficiency of legumes. Agricultural Water Management, 245, 106624. https://doi.org/10.1016/j.agwat.2020.106624
3. Allen, R. G., Pereira, L. S., Raes, D. & Smith, M. (1998). Crop Evapotranspiration: Guidelines for computing crop water requirements. Irrigation and Drainage Paper 56, FAO of the United Nations, Rome.
4. Amizero, E. (2018). Effect of Supplementary Sprinkler Irrigation on Growth and Yield of French Beans (Phaseolus Vulgaris L.) in Semi-arid Muvumba Valley, Rwanda. Master's dissertation, Faculty of Agriculture & Veterinary Medicine, University of Nairobi publisher.
5. Andales, A. A., Chávez, J. L., Bauder, T. A. & Arabi, M. (2015). Irrigation scheduling: The water balance approach. Colorado State University Extension Fact Sheet, No. 4.707. Colorado State University Extension.
6. Baker, H., & Yilmaz, A. (2020). Genetic variability and irrigation effects on yield and yield components in legumes. Journal of Crop Science, 60(3), 837–846. https://doi.org/10.2135/cropsci2019.06.0328
7. Blaney, H. F. & Criddle, W. D. (1950). Determining water requirements in irrigated areas from climatological and irrigation data. Technical Paper No. 96, United States Department of Agriculture, Soil Conservation Service, Washington. 44pp.
8. Chandra, A., Heeren, D., Odhiambo,L. & Brozović, N.(2023). Water-energy-food linkages in community smallholder irrigation schemes: Center pivot irrigation in Rwanda. Agricultural Water Management, 289(1),108506
9. Chaurasia, S. (2020). Green Beans. In K.J. Amit, (Eds.), Nutritional Composition and Antioxidant Properties of Fruits and Vegetables (pp. 289-300). Academic Press.
10. Christiansen, J. E. (1968). Pan evaporation and evapotranspiration from climatic data. J. Irrig. Drain. Divis., ASCE 94: 243-265.
11. Collins, D., Green, R. & Fox, L. (2021). Photosynthesis and nutrient transport efficiency under varied irrigation in bean cultivars. Plant Physiology and Biochemistry, 162, 279–288. https://doi.org/10.1016/j.plaphy.2020.12.012
12. DDS (2018). Huye District Development Strategy (2018– 2024). Huye district, Republic of Rwanda.
13. De Silva, P. & Rojas, M. (2021). Drought tolerance mechanisms in bean cultivars: Influence of genotype and irrigation. Journal of Agronomy, 13(2), 56–65. https://doi.org/10.3390/agronomy13020056

14. Delta-T Devices Ltd (2013). User Manual for the Moisture Meter: type HH2 V4.0.1. Delta-T Devices Ltd, Cambridge, UK.
15. Doorenbos, J. & Kassam, A. H. (1979). Yield Response to Water. FAO Irrigation and Drainage Paper, 33, 257.
16. Doorenbos, J. & Pruitt, W. O. (1975). Guidelines for predicting crop water requirements, Irrigation and Drainage Paper24, FAO of the United Nations, Rome. 179 pp.
17. Ertek, A. & Kara, B. (2013). Yield and quality of bell pepper under various irrigation regimes and grown with mulching. Journal of Agricultural Science and Technology, 15(5), 993-1003.
18. Ertek, A., Sensoy, S., Gedik, I. & Kucukyumuk, C. (2007). Irrigation scheduling for green pepper (Capsicum annuum L.) grown in field conditions by using class-A pan evaporation values. American-Eurasian J. Agric. Environ. Sci. 2(4), 349–358.
19. González, R. & Herrera, F. (2022). Conservation strategies in water-limited agriculture: The impact of deficit irrigation on legume yields. Agricultural Water Conservation Research, 38, 22–33. https://doi.org/10.1016/j.agwaconres.2021.102432
20. Gutiérrez, C., Santos, J. & Navarro, A. (2020). Assessing rainfed conditions and yield reductions in legume cropping systems. International Journal of Agronomy, 2020, 4219826. https://doi.org/10.1155/2020/4219826
21. Hakiruwizera, E. & Uçar, Y (2023). Effect of Different Irrigation Water Levels on Yield and Quality Parameters of Fodder Beet. KSU J. Agric Nat 26(3), 588-599. https://doi.org/10.18016/ksutarimdoga.vi.1168306
22. Johnson, R. & Patel, N. (2019). Yield enhancement in legumes under full irrigation: A meta-analysis. Water and Crop Science, 47(4), 285–296. https://doi.org/10.1016/j.wacs.2019.06.005
23. Kumar, V. & Fernandez, M. (2020). Maximizing growth in bean varieties through combined irrigation and genetic selection. Legume Research, 43(5), 622–629. https://doi.org/10.18805/lr-4301
24. Laishram, K.S., Roma, S. D., Chandramani, S., Hijam, J.S., Arati, N., T., Basanta, S. & Thoithoi, D. (2023). Evaluation of crop irrigation requirement of French bean (Phaseolus vulgaris L.) under varying meteorological conditions in Imphal West district of Manipur, northeast India. Indian Journal of Hill Farming, 36(1), 114-121.
25. Larochelle, C., Asare-Marfo, D., Birol, E., & Alwang, J. (2016). Assessing the Adoption of Improved Bean Varieties in Rwanda and the Role of Varietal Attributes in Adoption Decisions. Harvest Plus Working Paper.
26. Lim, H., Cho, K., & Lee, J. (2021). Sustainable yield strategies: Evaluating deficit irrigation in bean production. Water Resources in Agriculture 35(3),165–175.
27. Ma, Q., & Lin, Z. (2021). Legume productivity under water stress: Balancing irrigation with cultivar selection. Journal of Agricultural Research, 56(2), 120–130. https://doi.org/10.1016/j.jagr.2021.05.007
28. Magdoff, F. & Van Es, H. (2021). Building Soils for Better Crops. Sustainable Soil Management, 4th Ed, Sustainable Agriculture Research and Education (SARE) Program. National Institute of Food and Agriculture, (USDA). https://www.sare.org/wp-content/uploads/Building-Soils-for-Better-Crops.pdf
29. Martínez, A., & Singh, P. (2023). Water availability and nutrient uptake in beans under rainfed conditions. Journal of Plant Science, 14(1), 102–113. https://doi.org/10.1016/j.jps.2023.01.004
30. Mehta, R. & Pandey, V. (2016). Crop water requirement (ETc) of different crops of middle Gujarat. Journal of Agrometeorology 18 (1): 83-87.

31. NAEB. (2023). National handbook: February 2023 statistics report. National Agricultural Export Board (NAEB). Kigali.
32. NISR (2017). Statistical Yearbook, 2017 Edition. National Institute of Statistics of Rwanda, Kigali.
33. NISR. (2015). Agricultural Household Survey 2015 Report. National Institute of Statistic of Rwanda, Republic of Rwanda, Kigali.
34. NISR. (2021). Agricultural Household Survey 2020 Report. National Institute of Statistic of Rwanda, Republic of Rwanda, Kigali.
35. Onyango, P. (2021). Farmer preferred, market demanded and highly nutritious beans to boost Rwanda's household diets and wealth. Pabra. Retrieved on 07/08/2024. https://www.pabra-africa.org/farmer-preferred-market-demanded-and-highly-nutritious-beans-to-boost-rwandas-household-diets-and-wealth/
36. Osei, F., Mensah, K., & Abena, R. (2022). Comparative performance of bean cultivars under varying irrigation levels. International Journal of Agricultural Sciences, 89(3), 55–65.
37. Pereira, L.S., Paredes, P., & Jovanovic, N. (2020). Soil water balance models for determining crop water and irrigation requirements and irrigation scheduling focusing on the FAO56 method and the dual Kc approach. Agricultural Water Management, 241, 106357. https://doi.org/10.1016/j.agwat.2020.106357.
38. Pérez, L., Gutiérrez, S., & Fernandez, E. (2020). Yield and growth penalties in legumes under water-limited environments. Crop Science Journal, 51(2), 411–420. https://doi.org/10.2135/cropsci2020.01.0154
39. Raatz, B., Mukankusi, C., Lobaton, J. D., Male, A., Chisale, V., Amsalu, B., & He, C. (2019). Analyses of African common bean (Phaseolus vulgaris L.) germplasm using a SNP fingerprinting platform: diversity, quality control and molecular breeding. Genetic resources and crop evolution, 66(3), 707-722. https://doi.org/10.1007/s10722-019-00746-0.
40. Santos, R., Almeida, P., & Morais, J. (2023). Evaluating irrigation and variety interactions on yield in legume cropping systems. Agricultural Science Review, 12(4), 98–112.
41. Singh, N. I & Chauhan, J.S. (2009). Response of French bean (Phaseolus Vulgaris L.) To Organic Manures and Inorganic Fertilizer on Growth & Yield Parameters under Irrigated Condition. Nature and Science, 7 (5), 52-54. http://www.sciencepub.net
42. Smith, D., Jones, E., & Zhou, Y. (2020). Irrigation management and its influence on legume yield performance. Agronomy Journal, 112(5), 3812–3821. https://doi.org/10.2134/agronj2020.05.0241
43. Soil Survey Staff (1999). National Soil Survey Handbook, title 430-VI. United States.
44. Stewart, J.I., Hagan, R.M. & Pruitt, W.O. (1976). Production Functions and Predicted Irrigation Programs for Principal Crops as Required for Water Resources Planning and Increased Water use Efficiency. Tech. Bureau Recl. No: 14-06-D. 7329, USA.
45. Tan, K., Lee, H., & Goh, W. (2018). Impact of deficit irrigation on legume morphology and yield. Journal of Agronomy and Crop Science, 204(4), 387–397. https://doi.org/10.1111/jac.12233
46. Turc, L. (1961). Estimation of irrigation water requirements, potential evapotranspiration: A simple climatic formula evolved up to date. Ann. Agron.,12:13-49.
47. Uwanyirigira, J., Owido, F.O.O & Lelei, J.J. (2023). Influence of Irrigation Levels and Mulching Types on Growth and Yield of Bean in Drought Prone Area of Bugesera, Eastern Rwanda. American Journal of Agriculture, 5 (1), 22 – 41.

48. Wang, M., Liu, X., & Zhang, L. (2019). Rainfed versus irrigated conditions: A yield comparison in bean production. Agricultural Water Management, 218, 101–108. https://doi.org/10.1016/j.agwat.2019.03.007
49. Werner, H.D. (2002). Irrigation management using electrical resistance blocks to measure soil moisture. FS899. South Dakota State University, SDSU Extension. Available at http://pubstorage.sdstate.edu/AgBio_Publications/articles/FS899.pdf.