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Influence of Different Irrigation Regimes on Physiological Growth and Yield Parameters of *Stevia rebaudiana* Bertoni under Subtropical Agro-climatic Conditions

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Abstract**:** The present investigation was conducted at Division of Agroforestry, Sher-e-Kashmir University of Agricultural Sciences and Technology, Jammu, to determine the effect of different irrigation depths and IW:CPE ratios on the growth and leaf yield of *Stevia rebaudiana*. The experiment included ten treatments comprising various combinations of irrigation water depths (40 mm, 50 mm, 60 mm) and IW:CPE ratios (0.8, 1.0, 1.2), along with a rainfed control. The irrigation had significant influence on all measured growth and yield parameters. Among the treatments, irrigation at 60 mm depth with an IW: CPE ratio of 1.0 (T9) resulted in the highest plant height, number of branches and leaves per plant, as well as fresh and dry leaf yield. Although IW60mm: CPE=1.2 was statistically at par with T9, showed slightly reduced growth and yield, possibly due to waterlogging and nutrient leaching. In contrast, rainfed conditions recorded the lowest values for all parameters. The findings suggest that optimal irrigation not only enhances physiological growth but also contributes to higher biomass accumulation in *S. rebaudiana*. Therefore, irrigation with 60 mm water depth at an IW: CPE ratio of 1.0 is recommended for maximizing leaf yield under subtropical conditions. Additionally, applying three irrigations per month during the critical summer months (May–June) at 8–10-day intervals is suggested to maintain optimum soil moisture and ensure superior crop performance.

Keywords**:** Irrigation, IW: CPE ratios*, Stevia rebaudiana,* Steviol glycosides, Sweetener

Stevia rebaudiana Bertoni is a perennial shrub (Jahan et al., 2014) belonging to the family Asteraceae In native habitat, *Stevia rebaudiana* thrives in the semi-humid subtropical regions of Paraguay at elevations ranging from 200 to 400 meters above mean sea level, receiving annual rainfall between 1500–1800 mm, and typically growing on poor, sandy, acidic soils (Peteliuk et al., 2021). Beyond native environment, the crop has been successfully cultivated across a broad range of climatic zones in countries such as China, Japan, Canada, Vietnam, Taiwan, South Korea, USA, India, Thailand, Russia, Spain, Italy, Germany, and Sweden (Razak et al., 2014, Miladinova-Georgieva et al., 2022). In India, *Stevia* is well-suited to the southern climate and is commercially cultivated, with recent expansion into the northern plains and mid-hill regions. The crop shows good adaptability to the subtropical and sub-temperate conditions of the Jammu region under irrigated conditions. Morphologically, the plant attains a height of 65 to 75 cm and bears sessile, oppositely arranged lanceolate to oblanceolate leaves that are serrated above the middle. The flowers are small, white, and arranged in an irregular cyme. With growing consumer awareness of the health risks associated with high sugar intake, there is a rising preference for food products containing natural sweeteners. *Stevia*, as a zero-calorie, low-glycemic sweetener, has emerged as a promising natural substitute for sugar and synthetic sweeteners like saccharin, aspartame, and acesulfame-K, especially given the global diabetic population exceeding 346 million. The leaves of *Stevia* are rich in two primary steviol glycosides (Peteliuk et al., 2021). One of the most significant developments in *Stevia* research is understanding the role of irrigation management not just on yield but also the composition of steviol glycosides (Shivanna et al., 2013). The irrigation criteria based on soil water tension affects both leaf yield and the specific composition of steviol glycosides (Parris et al., 2017). This finding is crucial for commercial production, as different glycosides have varying sweetness intensities and market values. The relationship between water availability and glycoside production appears to be complex, with moderate water stress potentially enhancing the concentration of certain compounds while excessive stress reduces overall productivity (Tadhani et al., 2007). This balance is critical for optimizing both the economic return and the functional quality of stevia leaves. To promote its commercial cultivation, it is crucial to standardize agronomic practices across different agro-climatic regions. Among these, irrigation management, popularly advocated as precision silviculture in forestry tree and medicinal plants species is a critical factor influencing biomass and yield. (Luna et al., 2011, Jagani et al., 2020, Shrivastava et al., 2025). *Stevia* requires careful irrigation management and is sensitive to water quality (Reis et al., 2015). The development of region-specific irrigation schedules is essential for optimizing its production.

MATERIAL AND METHODS

The investigation was conducted at Division of Agroforestry, Sher-e-Kashmir University of Agricultural Sciences and Technology, Chatha, Jammu. The site is situated within the university campus at an elevation of 332 meters above mean sea level, located at 32°40′ N latitude and 74°58′ E longitude. The experimental area falls under the sub-tropical zone of Jammu division in Jammu and Kashmir State, characterized by hot dry summers, hot humid rainy seasons, and cold winters. The region receives an average annual rainfall of approximately 1000–1200 mm, with about 75–80% occurring between July and September and the remaining 20–25% during the winter months from December to February. The temperature in this region can rise above 40°C during May to August, while it may drop as low as 3°C in the winter season (Fig. 1).

The experiment was laid out in a randomized block design comprising ten treatments with three replications. Raised beds measuring 1.5 × 1.0 m² were prepared, and seedlings were planted at a spacing of 25 cm × 50 cm. Three irrigation water depths 40 mm, 50 mm, and 60 mm were used to achieve IW:CPE ratios of 0.8, 1.0, and 1.2 for each depth level. Daily pan evaporation and rainfall data were recorded throughout the study. To achieve the desired IW:CPE ratios, irrigation was applied when cumulative pan evaporation reached specific thresholds. For the 40 mm depth, irrigation was applied after 50 mm, 40 mm, and 33.33 mm of cumulative pan evaporation to maintain IW:CPE ratios of 0.8, 1.0, and 1.2, respectively. Similarly, for the 50 mm depth, irrigation was scheduled after 62.5 mm, 50 mm, and 41.6 mm of pan evaporation, and for the 60 mm depth, after 75 mm, 60 mm, and 50 mm of cumulative evaporation. Observations were recorded on various growths and yield attributes, including plant height (cm), number of branches per plant, stem diameter (mm), number of leaves per plant, fresh and dry leaf yield per plant (g), and estimated fresh and dry leaf yield per hectare (q). Data were collected from 15 randomly selected plants per treatment to assess treatment effects.

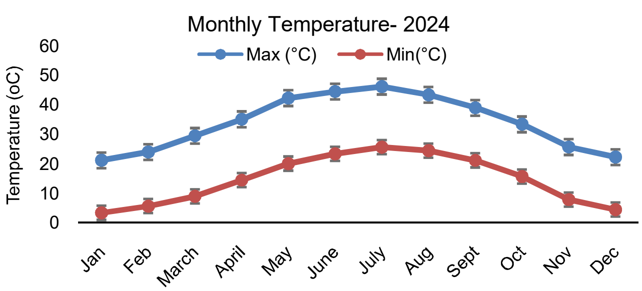

Fig. 1. Monthly temperature of Jammu region

RESULTS AND DISCUSSION

Mean performance of growth and yield attributes as affected by irrigation: The irrigation had significant and positive impact on the growth and leaf yield of *S. rebaudiana* (Table 2). Among the various irrigation treatments, T_9 (IW60mm: CPE60mm = 1.0) showed enhancement in growth parameters, but was statistically at par with T_{10} (IW60mm: CPE50mm = 1.2). Both treatments received five irrigations during the six-month growth period, two irrigations in May and three in June. The irrigation schedule T_9 not only improved vegetative growth but also substantially enhanced leaf yield. In 40 mm and 50 mm irrigation depths, while there was a gradual increase in growth and yield attributes with increasing IW:CPE ratios, the differences between the 0.8 and 1.0 ratios were not statistically significant. The highest plant height, number of branches per plant, and number of leaves per plant were recorded under T_9, and although slightly lower. Similar trend was observed in T_{10}, indicating statistical parity between the two. The fresh and dry leaf yield were significantly influenced by irrigation schedules, with T_9 producing the highest dry leaf yield per hectare (5.58 q), which was also statistically similar to T_{10}.

There was strong positive linear relationship between irrigation schedule and plant height, where plant height increases with higher irrigation levels, directly influencing growth and yield parameters (Fig. 2). The very strong relation between plant height and number of branches, ($y=0.7806x-26.531y$) show that each 1 cm increase in height adds about 0.78 branches($R^2=0.9649$) which explains 96.5% of the variation. The strong positive correlation between plant height and dry leaf yield was observed ($R^2=0.9681$), where yield rises by about 0.14 units per cm increase in height (Fig. 2 b). There was weak correlation between plant height and stem diameter ($R^2=0.529$), only 53% of the variation is explained (Fig. 2c). The plant height is strongly correlated with number of leaves ($R^2=0.962$), adding about 7.4 leaves per cm growth (Fig. 2d). Similarly, there was strong positive correlation between plant height and fresh leaf yield ($R^2=0.9622$), with about 0.47 units of fresh yield gained per cm increase in height (Fig. 2e).

Aladakatti et al. (2012b) also reported that irrigation at IW60mm: CPE60mm = 1.0 is optimal for maximizing dry leaf yield and water use efficiency in *S. rebaudiana*. However, the dry leaf yield reported was considerably higher (10.54 t ha^{-1}) compared to the current study. This discrepancy may be attributed to differences in the growing period at the respective locations-Jammu and Belavatagi (Karnataka).

Additionally, the current study involved only a single harvest after six months, whereas Aladakatti et al. (2012b) recorded five harvests annually, which likely contributed to increased branching, foliage, and overall yield. Mahajan and Pal (2022) reported that the dry leaf and total steviol glycosides (SGs) yield of stevia was maximum with the irrigation at 50 kPa. At harvest, the plants irrigated at 50 kPa produced 26.9-32.5% higher dry matter over limited application of water (75 kPa). Recent research has significantly advanced our understanding of irrigation management in *S. rebaudiana* cultivation, particularly in the context of precision irrigation technologies and climate adaptation strategies (Abdelsattar et al., 2024). Studies conducted in cooler climates, such as Poland, demonstrated

Table 1. Treatments with different levels of irrigation

Treatment no.	Irrigation schedule
T_1	Control (Rainfed)
T_2	IW_{40mm}: CPE_{50mm}=0.8
T_3	IW_{40mm}: CPE_{40mm}=1.0
T_4	IW_{40mm}: $CPE_{33.33mm}$=1.2
T_5	IW_{50mm}: $CPE_{62.5mm}$=0.8
T_6	IW_{50mm}: CPE_{50mm}=1.0
T_7	IW_{50mm}: $CPE_{41.6mm}$=1.2
T_8	IW_{60mm}: CPE_{75mm}=0.8
T_9	IW_{60mm}: CPE_{60mm}=1.0
T_{10}	IW_{60mm}: CPE_{50mm}=1.2

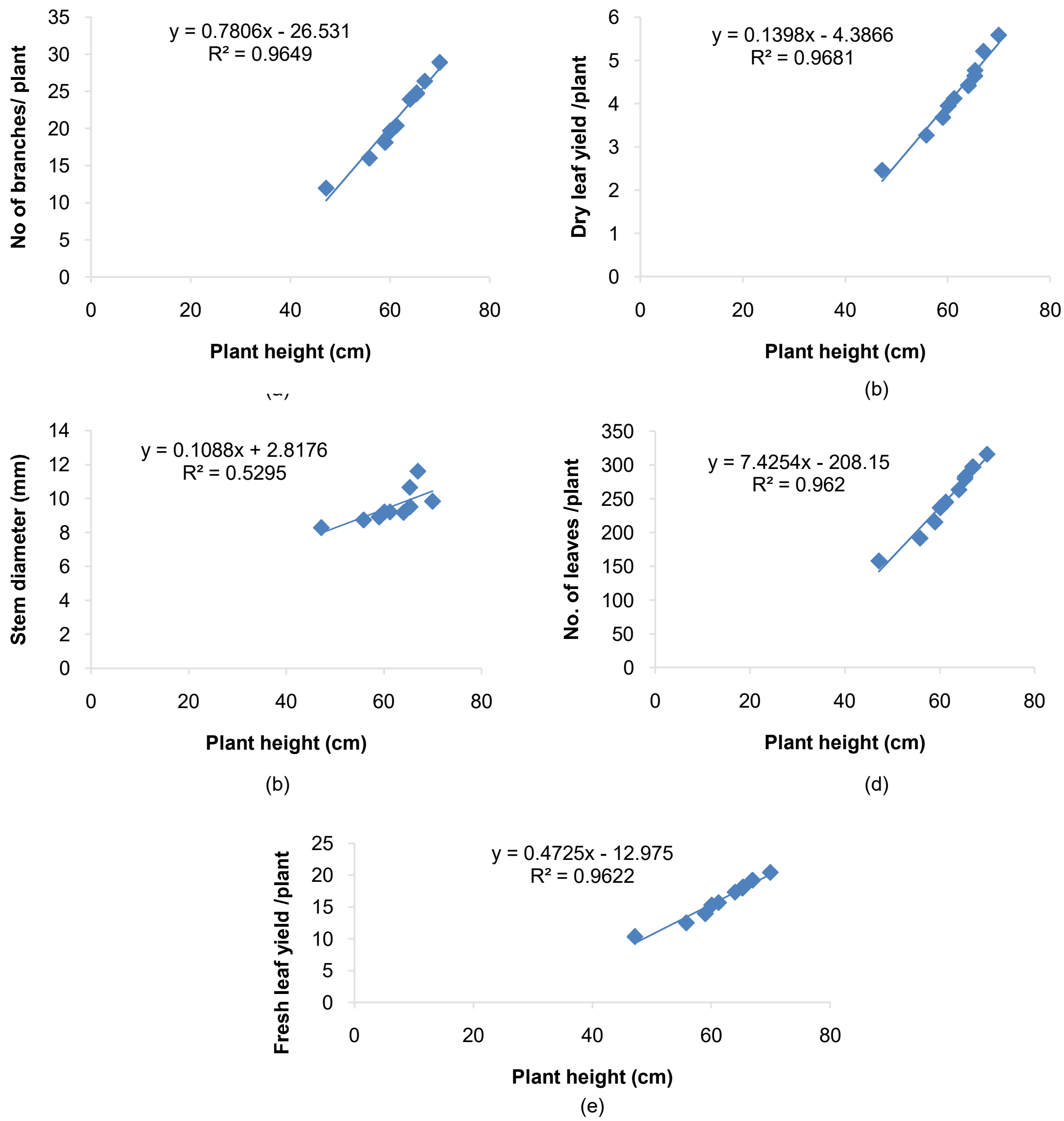

Fig. 2. Relationship between irrigation schedule, plant height and other parameters of plant growth and yield

that different irrigation practices can significantly influence both yield and composition of stevia leaves when grown outside their native warm climate regions (Ceunen and Geuns 2013). This finding is particularly relevant for expanding stevia cultivation to temperate regions where water management becomes even more critical. The superiority of the 60 mm irrigation depth over the 50 mm and 40 mm treatments can be attributed to the consistent moisture availability during critical growth stages, facilitating better root development and enhanced nutrient uptake, which ultimately led to improved growth and productivity. This observation aligns with the findings of Acevedo and Kalra et al. (2024), which emphasized the role of water in root development and cell elongation. Conversely, limited water availability in 40 and 50 mm treatments likely caused moisture stress, reducing growth and yield. Singh (2009) also reported that water stress inhibits plant growth by limiting cell enlargement.

Table 2. Effect of irrigation on growth and yield parameters

Treatments/ Irrigation levels	Plant height (cm)	No. of branches plant	Stem diamete (mm)	No. of leaves plant^{-1}	Leaf yield plant^{-1} (gm)		Leaf yield (q ha^{-1})	
					Fresh	Dry	Fresh	Dry
T_1 (Rainfed)	47.18	11.96	8.28	158.07	12.94	3.08	10.35	2.46
T_2 (IW_{40mm}/CPE=0.8)	55.83	16.02	8.73	191.53	15.64	4.09	12.51	3.27
T_3 (IW_{40mm}/CPE=1.0)	59.01	18.12	8.91	215.29	17.43	4.60	13.95	3.68
T_4 (IW_{40mm}/CPE=1.2)	60.09	19.68	9.20	236.72	19.13	4.94	15.30	3.95
T_5 (IW_{50mm}/CPE=0.8)	61.26	20.39	9.21	244.88	19.60	5.16	15.68	4.12
T_6 (IW_{50mm}/CPE=1.0)	64.02	23.91	9.17	263.33	21.67	5.52	17.33	4.42
T_7 (IW_{50mm}/CPE=1.2)	65.29	24.63	10.65	279.52	22.42	5.80	17.93	4.64
T_8 (IW_{60mm}/CPE=0.8)	65.35	24.78	9.51	282.54	22.65	5.97	18.12	4.77
T_9 (IW_{60mm}/CPE=1.0)	69.97	28.89	9.83	315.95	25.54	6.98	20.43	5.58
T_{10} (IW_{60mm}/CPE=1.2)	66.96	26.36	11.60	297.06	23.98	6.51	19.21	5.21
CD (p=0.05)	8.60	3.63	NS	33.34	2.73	0.57	2.19	0.46

Table 3. Effect of irrigation on growth and yield parameters of stevia

Source / Study	Irrigation treatments	Observed growth/yield	Key insights
Irrigation on growth and yield parameters in Subtropical Agro-climatic Conditions of India	Rainfed to IW_{40mm}/CPE=0.8, 1,1.2, IW_{50mm}/CPE = 0.8, 1,1.2 IW_{60mm}/CPE=0.8, 1,1.2	IW_{60mm}/CPE=1.0resulted in the highest plant height, number of branches and leaves per plant, as well as fresh and dry leaf yield.	Providing three irrigations per month during the critical summer period (May–June) at intervals of 8–10 days is recommended (Current study)
Irrigation regimes in Southern Italy	T33 (~33% irrigation), T66 (~66%), T100 (full irrigation)	Dry leaf yield increased by ~40% at full irrigation (T100) compared to minimal (T33). Harvest index & water-use efficiency (WUE) decreased as irrigation increased. Leaf glycoside content remained unchanged across treatments.	Full irrigation boosts yield, but can lower efficiency; quality stable (Lavini et al., 2008).
Irrigation frequency in Poland (cool climate)	No irrigation, irrigation once per week, irrigation twice per week, irrigation only during drought	Highest yields (2.42–2.58 kg/m²) were achieved with irrigation once per week or during drought. Un-irrigated plants were shortest and narrowest; had higher dry mass and more phenolics. Irrigated plants had lower chlorophyll & carotenoid levels at harvest.	Regular irrigation enhances biomass but influences leaf chemistry (Śniegowska et al., 2024)
Soil Water Tension (SWT) criteria in US cultivars	Drip irrigation thresholds (10, 20, 40, 60, 80 kPa)	Wetter criteria (lower tension) generally led to increased dry leaf yield and steviol glycoside traits; but results were not always statistically clear—although linear trends were significant.	Greater soil moisture tends to enhance yield and quality glycosides (Parris et al., 2017).
Supplementary irrigation during flowering and seeding	Addition of two supplementary irrigations in greenhouse/farm settings	Supplementary irrigation at critical stages (flowering and seeding) significantly improved sugar (presumably stevioside) yield.	Targeted irrigation at critical stages enhances yield efficiency (Ghamarnia et al., 2022).

Contemporary research has revealed that *S. rebaudiana* exhibits complex physiological responses to water stress that directly impact both biomass accumulation and steviol glycoside production (Shahverdi et al., 2019). Studies from Morocco have shown that water stress significantly affects growth, yield, quality, and physiological responses of different stevia varieties. The plant's response to water deficit involves alterations in leaf morphology, stomatal behaviour, and metabolic processes that ultimately influence the concentration of sweet compounds in the leaves (Zeng et al., 2013). Interestingly, despite receiving fewer irrigations, T_9 outperformed T_6 (IW50mm/CPE50mm = 1.0) and T3 (IW40mm/CPE40mm = 1.0), likely due to the higher irrigation water depth in T_9, which maintained soil moisture for longer periods and effectively compensated for evapotranspiration losses. The increase in branches, leaf count, and leaf yield in T_9 was nearly double that of the rainfed control, underscoring the significant role of irrigation. Although T_{10} had the highest irrigation frequency under 60 mm depth, T_9 produced better growth and yield, possibly because excessive irrigation in T_{10} may have led to nutrient leaching and waterlogging, which could negatively impact root respiration and nutrient uptake, ultimately reducing photosynthesis.

CONCLUSION

The study demonstrates that irrigation levels have a significant impact on the vegetative growth and leaf yield of the crop. The irrigation with a depth of 60 mm at an IW:CPE ratio of 1.0 proved to be the most effective in enhancing plant growth characteristics such as height, branching, number of leaves, and overall leaf biomass. This treatment consistently outperformed others in terms of fresh and dry leaf yield per plant and estimated yield per hectare, indicating its superiority under the given agro-climatic conditions. In contrast, rainfed conditions led to the lowest performance across all growth and yield parameters, emphasizing the importance of timely and adequate irrigation. The irrigation at 60 mm depth with an IW:CPE ratio of 1.0 is optimal for maximizing leaf yield**.** Additionally, providing three irrigations per month during the critical summer period (May-June) at intervals of 8-10 days is recommended for achieving better productivity under similar soil and climatic conditions.

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