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Scientific Article

Effect of babassu mesocarp hydrogel on the initial development of watermelon seedlings

Efeito do hidrogel de mesocarpo de babaçu no desenvolvimento inicial de mudas de melancia

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ABSTRACT – This study evaluated the effects of babassu mesocarp hydrogel doses and irrigation frequency on the initial growth and water use efficiency (WUE) of *Citrullus lanatus* ('Crimson Sweet') seedlings in a completely randomized 2 × 5 factorial design, combining two irrigation intervals (24 and 48 h) and five doses of swollen hydrogel (0, 10, 20, 30, and 40 g per container, corresponding to 0, 40, 80, 120, and 160 mg of dry hydrogel). Under the 48-h irrigation regime, WUE increased from 0.000077 g mL^{-1} in the control to 0.000198 g mL^{-1} at the highest hydrogel dose, corresponding to a 157.1% increase. Under daily irrigation (24 h), WUE increased linearly with hydrogel dose, although the magnitude of this response was lower than under the 48-h irrigation interval. At the 48-h irrigation interval, increasing hydrogel doses linearly increased root length, stem diameter, fresh mass, total dry mass, and water use efficiency. Under daily irrigation, biomass accumulation showed no consistent dose-dependent response, and no significant linear or quadratic dose-response pattern was detected for most growth variables. At the 48-h irrigation interval, the highest hydrogel dose resulted in the highest numerical total dry mass and water use efficiency among the treatments within this irrigation regime, whereas increasing hydrogel doses under daily irrigation did not result in a consistent dose-dependent improvement in early shoot development.

Keywords: Water use efficiency. Irrigation frequency. Sustainable management.

RESUMO – Este estudo avaliou os efeitos de doses de hidrogel de mesocarpo de babaçu e da frequência de irrigação sobre o crescimento inicial e a eficiência no uso da água (EUA) de mudas de *Citrullus lanatus* ('Crimson Sweet'), em delineamento inteiramente casualizado, em esquema fatorial 2 × 5, com dois intervalos de irrigação (24 e 48 h) e cinco doses de hidrogel hidratado (0, 10, 20, 30 e 40 g por recipiente, correspondentes a 0, 40, 80, 120 e 160 mg de hidrogel seco). Sob irrigação de 48 h, a EUA aumentou de 0,000077 g mL^{-1} no controle para 0,000198 g mL^{-1} na maior dose, correspondendo a um aumento de 157,1%. Sob irrigação diária (24 h), a EUA aumentou linearmente com a dose, embora a magnitude dessa resposta tenha sido menor. No intervalo de irrigação de 48 h, o aumento das doses promoveu incrementos lineares no comprimento da raiz, diâmetro do caule, massa fresca, massa seca total e EUA. Sob irrigação diária, o acúmulo de biomassa não apresentou resposta consistente em função da dose, e nenhum padrão linear ou quadrático significativo foi detectado para a maioria das variáveis de crescimento. No intervalo de irrigação de 48 h, a maior dose resultou no maior valor numérico para a massa seca total e a EUA, enquanto, sob irrigação diária, o aumento das doses não promoveu melhoria consistente e dependente da dose no desenvolvimento inicial da parte aérea.

Palavras-chave: Eficiência no uso da água. Frequência de irrigação. Manejo sustentável.

Conflict of interest: The authors declare no conflict of interest related to the publication of this manuscript.

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INTRODUCTION

In 2015, the United Nations (UN) established the 17 Sustainable Development Goals (SDGs), which constitute a global call to promote economic growth decoupled from poverty, social inequality, and climate change. Within the context of Brazil's 2030 Agenda, priorities include eradicating hunger, promoting sustainable agriculture, ensuring health and well-being, providing access to clean water, encouraging responsible consumption, and preserving the water sources and the environment (UNITED NATIONS, 2015). In this scenario, chemistry plays a fundamental role in the development of innovative technologies and materials. Among these, polymer technology stands out due to its wide-ranging applications in fields such as medicine, engineering, and agriculture (OLIVEIRA et al., 2023; ELMOWAFY et al., 2023; AZEEM et al., 2023).

The SDGs face increasingly complex challenges, particularly due to the growing demand for water and food driven by population growth. In containerized seedling production, factors such as limited substrate volume, rapid drainage, and high nutrient leaching significantly contribute to reduced water availability and declining fertility of the growing medium. In this context, the search for strategies that promote the efficient use of water resources becomes essential, especially in nursery management under arid and semi-arid conditions.

Among the promising alternatives, superabsorbent hydrogel-based polymers stand out due to their three-dimensional hydrophilic structure, which enables the storage of water and nutrients with gradual release into the growing medium. In addition to reducing irrigation frequency and volume, these materials contribute to maintaining water and nutrient availability, thereby promoting initial seedling development (DAS; BHATTACHARJEE; BHALADHARE, 2023; KRASNOPEEVA; PANOVA; YAKIMANSKY, 2022).

Hydrogels valued for environmental and agricultural applications generally possess biodegradability, sustainability, low toxicity, and cost-effectiveness. Those based on natural polysaccharides (such as cellulose, starch, pectin, chitosan, and gums) stand out due to their abundance and renewability (GUILHERME et al., 2015). A promising example is the hydrogel obtained from the mesocarp of babassu (*Orbignya phalerata*), a native and abundant plant in the mid-north region of Brazil, especially in the states of Piauí and Maranhão. The babassu mesocarp contains up to 70% starch, varying according to the plant's maturity stage, making it an attractive raw material to produce superabsorbent hydrogels (SOUSA et al., 2023). Specifically, this material is synthesized via the graft copolymerization of the babassu mesocarp with polyacrylamide, creating a three-dimensional hydrophilic matrix. According to Sousa et al. (2023), this hydrogel exhibits a high superabsorbent capacity, with an equilibrium swelling degree ranging from 250 to 300 g/g, while maintaining structural integrity and a non-toxic safety profile. These properties establish the polymer as an excellent sustainable moisture reservoir tailored for containerized substrate enhancement.

Although numerous studies highlight the potential of hydrogels in agriculture, their practical application remains underexplored. Conducting controlled seedling experiments, particularly with crops that have high water demand such as watermelon, is essential to assess the effectiveness of these materials during early developmental stages. Watermelon cultivation in regions characterized by irregular rainfall faces major challenges related to water deficits during nursery management and the production of high-quality seedlings for field transplantation. The incorporation of hydrogels into the substrate emerges as an effective strategy to mitigate these challenges, as it can reduce irrigation requirements and consequently enhance initial growth parameters (PEREIRA et al., 2019).

Considering the above, this study evaluated the application of superabsorbent hydrogel polymers produced from babassu mesocarp as an innovative solution to optimize watermelon seedling development in environments with limited water availability. The objective was to assess the effects of different hydrogel doses on the early growth and water use efficiency of the seedlings under 24- and 48-hour irrigation intervals.

MATERIAL AND METHODS

The experiment was conducted between August and September 2024 at the Practical Classes and Research Unit (UAPP) of the Federal Institute of Piauí, Valença Campus (6° 24' 27" S; 41° 44' 44" W; altitude 74.4 m). According to Köppen's classification, the climate is BSh (hot semi-arid tropical) (ALVARES et al., 2013). During the trial, inside the nursery, the average temperature ranged from 27.5 °C to 34.8 °C, the relative humidity remained between 38% and 52%, and no rainfall occurred.

The experiment was arranged in a completely randomized design, in a 2 × 5 factorial scheme, with four replications, resulting in a total of 40 experimental units (10 treatments × 4 replications). The first factor corresponded to the irrigation interval (watering every 24 or 48 hours), and the second factor to the swollen hydrogel doses (0, 10, 20, 30, and 40 g per container). Each experimental unit consisted of a group of four containers with one plant each, which were analyzed as sub-samples to obtain the mean value per replication. Therefore, each treatment comprised 16 plants, totaling 160 plants in the entire study.

The babassu mesocarp-based polysaccharide hydrogel was produced according to the methodology described by Sousa et al. (2023). Prior to its incorporation into the substrate, the dry hydrogel was pre-hydrated using distilled water at 25 °C for a continuous saturation period of 180 minutes to reach its equilibrium swelling degree. The resulting swollen gel was then passed through a calibrated mesh sieve to standardize the hydrogel particles into a uniform granular size of approximately 2.0 to 3.0 mm, avoiding agglomeration. During sowing, standardized doses of swollen hydrogel granules (Table 1) were applied as a circular ring (approximately 3.0 cm in diameter) around each watermelon seed, favoring localized moisture availability near the future rhizosphere. The precise volume of distilled water embedded within the pre-hydrated hydrogel matrix for each treatment dose was accounted for and included in the cumulative water supply volume used as the denominator to calculate water use efficiency (WUE), preventing overestimation of this index. The corresponding swollen hydrogel doses (10, 20, 30, and 40 g) were obtained from 40, 80, 120, and 160 mg of dry hydrogel, respectively. Based on the difference between dry and swollen masses, the estimated water volumes incorporated into the hydrogel were 9.96, 19.92, 29.88, and 39.84 mL, respectively. Considering that the procedure was conducted at approximately 25 °C, water mass (g) was directly converted into volume (mL).

Seeds of the Crimson Sweet watermelon cultivar, supplied by Horticeres Sementes, were sown in 500 mL polyethylene cups filled with a substrate composed of cured cattle manure and rice husk in a 1:1 (v/v) ratio. Rice husk is widely used as a substrate component due to its low bulk density, high aeration capacity, rapid drainage, and pH close to neutrality (STEFFEN et al., 2010). The containers were placed on a wooden bench suspended 1.20 m above the ground and covered with a black shade cloth providing 25% shading. This shading level was selected to mitigate microclimatic heat stress on the emerging seedlings during the hot dry season, while ensuring sufficient photosynthetically active radiation to prevent etiolation (PEREIRA et al., 2019). The seedlings remained in the containers for 20 days, corresponding to the initial growth stage.

Table 1. Experimental treatments showing the codes, dry and swollen hydrogel doses per container, water absorption, initial irrigation volumes, and irrigation intervals used in the study.

Code	Dry hydrogel dose (mg container^{-1})	Swollen hydrogel dose (g container^{-1})	Water absorbed by hydrogel (mL)	Initial irrigation water volume (mL)	Irrigation interval (h)
T1H0	0	0	-	100	24
T2H0	0	0	-	100	48
T1H10	40	10	9.96	90.04	24
T2H10	40	10	9.96	90.04	48
T1H20	80	20	19.92	80.08	24
T2H20	80	20	19.92	80.08	48
T1H30	120	30	29.88	70.12	24
T2H30	120	30	29.88	70.12	48
T1H40	160	40	39.84	60.16	24
T2H40	160	40	39.84	60.16	48

Irrigation management was carried out according to the established intervals, with crop water requirements determined directly via the gravimetric method through daily mass balance weighing. Daily, two individual containers were randomly selected from each of the four replications within each treatment (totaling 8 monitored containers per treatment, representing 50% of the experimental units) and weighed on a precision scale (0.01 g accuracy) to quantify water loss based on mass variation. The mean water depletion calculated within each replication was utilized to determine the specific replenishment volume for that plot, accounting for microclimatic spatial variations across the suspended bench. The container water-holding capacity was operationally determined prior to the experiment by saturating the substrate with a total initial volume of 100 mL of water (combining the water used for hydrogel pre-hydration and the initial irrigation volume, as detailed in Table 1), allowing free gravitational drainage through the bottom drainage holes until constant weight was reached, thus establishing the maximum water retention capacity under the experimental conditions. Irrigation was performed manually, and the volume replenished to meet water demand was controlled by weighing. In the daily irrigation treatment, replenishment occurred every day, whereas in the alternate-day irrigation treatment, it was performed every two days (Table 1). The total applied irrigation (TAI) was calculated as the sum of the initial 100 mL water supply and all subsequent water-replenishment volumes applied throughout the 20-day experimental period. These replenishment volumes were determined by gravimetric water-loss measurements and included all successive irrigation events.

Twenty days after sowing, the following parameters were evaluated: plant height (cm), stem diameter (mm), fresh and dry shoot mass (g), root length (cm), total dry mass (TDM), relative dry matter content (DM%), and water use efficiency (WUE, g mL^{-1}). Length measurements were taken using a millimeter ruler, while stem diameter was measured with a digital caliper with a precision of 0.01 mm. Fresh and dry masses were determined on a precision balance (±0.001 g); samples for dry mass analysis were oven-dried with forced air circulation at 65 °C until constant weight was achieved. Relative dry matter content (DM%) was calculated as the ratio between dry mass and fresh mass, expressed as a percentage [DM% = (dry mass/fresh mass) × 100]. Total dry mass (TDM) was operationally defined and calculated based on the dried aboveground biomass (shoots), as root dry mass was not determined due to the technical limitations of completely separating the fine root system from the hydrogel-substrate matrix. Additionally, physiological and growth parameters were assessed, including the total chlorophyll content, expressed as the Falker Chlorophyll Index (FCI) based strictly on the cumulative total index for the statistical analysis and results, and leaf number. All analyses were performed at the Agricultural Laboratory of the Federal Institute of Piauí, Valença Campus, Piauí state (Brazil).

Water use efficiency (WUE) for dry matter production was calculated according to Equation 1:

$$WUE = \frac{TDM}{TAI} \quad (1)$$

where:
WUE = water use efficiency (g mL^{-1});
TDM = total dry mass (g);
TAI = Total Applied Irrigation, calculated as the cumulative volume of irrigation water applied throughout the experimental period and expressed in milliliters (mL). The cumulative irrigation volume was also expressed as irrigation depth (mm). For this conversion, the container surface area (60.13 cm²), corresponding to the upper internal area of the standard 500-mL disposable container used in the experiment, was considered according to the equation: Irrigation depth (mm) = [Applied water volume (mL) / Container surface area (cm²)] × 10.

The results were expressed as mean ± standard deviation. To compare mean values, analysis of variance (ANOVA) was performed, followed by Tukey's test at a 5% significance level ($p < 0.05$). The effects of irrigation intervals and different hydrogel doses were evaluated by factor analysis and polynomial regression. Model selection considered the statistical significance of regression coefficients ($p < 0.05$) and biological parsimony. Additionally, the coefficient of determination (R^2) was used as a complementary measure of explanatory power. Residual plots were examined to assess

normality, homoscedasticity, and the absence of systematic patterns, ensuring that model assumptions were met. All statistical analyses were conducted using R software, version 4.4.0.

RESULTS AND DISCUSSION

A significant interaction between hydrogel dose and irrigation interval was observed for all evaluated parameters in watermelon seedlings, indicating that the response to hydrogel application depends on irrigation frequency. Physiological variables, such as the Falker Chlorophyll Index (FCI) and water use efficiency (WUE), as well as biometric and morphological parameters, including plant height (PH), fresh mass (FM), total dry mass (TDM), root length (RL), stem diameter (SD), number of leaves (NL), and dry matter content (DM%), varied according to the combinations of treatments. These results highlight that the effects of hydrogel on plant growth and water use depend on irrigation frequency. The interactions for each variable are discussed below, based on the data presented in Table 2 and the corresponding figures.

Table 2. Parameters of 'Crimson Sweet' watermelon seedlings evaluated under different irrigation intervals and doses of hydrogel based on polysaccharides from babassu mesocarp. ID: sample identifier; PH: plant height; FCI: Falker Chlorophyll Index; FM: fresh mass; TDM: total dry mass; TAI: total applied irrigation; WUE: water use efficiency; RL: root length; SD: stem diameter; NL: number of leaves; DM%: dry matter content. Within each column, means followed by the same lowercase letter do not differ according to Tukey's test ($p \leq 0.05$).

ID	PH (cm)	FCI	FM (g)	TDM (g)	TAI (mL)	WUE (g mL^{-1})	RL (cm)	SD (mm)	NL	DM (%)
T1H0	8.2 ± 0.3^{ab}	30.0 ± 1.3^{de}	0.802 ± 0.016^{a}	0.077 ± 0.001^{ab}	1487 ± 55^{a}	0.000052 ± 0.000000^{g}	20.2 ± 0.7^{cde}	3.00 ± 0.00^{a}	3.75 ± 0.20^{a}	9.47 ± 0.39^{c}
T2H0	8.3 ± 0.2^{ab}	27.5 ± 2.9^{ef}	0.615 ± 0.040^{de}	0.063 ± 0.006^{c}	816 ± 112^{b}	0.000077 ± 0.000004^{f}	17.0 ± 1.6^{f}	2.00 ± 0.00^{f}	3.33 ± 0.24^{bcd}	10.33 ± 0.50^{bc}
T1H10	8.0 ± 0.4^{abc}	38.5 ± 2.4^{a}	0.660 ± 0.045^{cde}	0.069 ± 0.003^{bc}	915 ± 34^{b}	0.000075 ± 0.000008^{f}	18.3 ± 1.3^{def}	2.71 ± 0.21^{abc}	3.15 ± 0.17^{d}	10.83 ± 0.59^{ab}
T2H10	8.2 ± 0.4^{ab}	24.6 ± 1.4^{f}	0.614 ± 0.009^{e}	0.064 ± 0.005^{c}	601 ± 59^{c}	0.000106 ± 0.000004^{de}	19.6 ± 1.0^{cdef}	2.11 ± 0.19^{ef}	3.25 ± 0.25^{cd}	10.49 ± 0.61^{abc}
T1H20	7.8 ± 0.4^{bc}	37.0 ± 3.1^{ab}	0.744 ± 0.047^{ab}	0.082 ± 0.003^{a}	807 ± 33^{b}	0.000102 ± 0.000005^{de}	17.8 ± 1.4^{ef}	2.56 ± 0.13^{bcd}	3.25 ± 0.20^{cd}	10.88 ± 0.53^{ab}
T2H20	7.3 ± 0.5^{cd}	31.1 ± 2.9^{cde}	0.625 ± 0.034^{de}	0.072 ± 0.006^{abc}	567 ± 72^{c}	0.000127 ± 0.000009^{c}	23.2 ± 1.6^{ab}	2.40 ± 0.13^{cde}	3.25 ± 0.20^{cd}	11.43 ± 0.57^{a}
T1H30	8.3 ± 0.4^{ab}	33.5 ± 2.5^{bcd}	0.720 ± 0.034^{bc}	0.079 ± 0.004^{ab}	806 ± 18^{b}	0.000098 ± 0.000004^{e}	22.0 ± 2.1^{bc}	2.73 ± 0.21^{abc}	3.71 ± 0.21^{ab}	10.98 ± 0.75^{ab}
T2H30	7.4 ± 0.4^{cd}	30.4 ± 1.7^{de}	0.680 ± 0.030^{bcd}	0.075 ± 0.006^{ab}	447 ± 52^{d}	0.000168 ± 0.000008^{b}	21.2 ± 0.3^{bcd}	2.31 ± 0.13^{def}	3.81 ± 0.24^{a}	11.08 ± 0.55^{ab}
T1H40	8.7 ± 0.5^{a}	34.9 ± 1.4^{abc}	0.706 ± 0.029^{bc}	0.072 ± 0.010^{abc}	649 ± 34^{c}	0.000111 ± 0.000009^{d}	23.9 ± 2.1^{ab}	2.92 ± 0.14^{ab}	3.64 ± 0.13^{abc}	10.09 ± 0.27^{bc}
T2H40	6.7 ± 0.2^{d}	29.5 ± 1.9 ^{de}	0.712 ± 0.027^{bc}	0.079 ± 0.005^{ab}	400 ± 43^{d}	0.000198 ± 0.000007^{a}	26.1 ± 1.9^{a}	2.42 ± 0.20^{cde}	3.79 ± 0.14^{a}	11.15 ± 0.71^{ab}

Analysis of variance (ANOVA) indicated that the interaction between irrigation interval and hydrogel dose (II × HD) had a significant effect ($p \leq 0.05$) on all evaluated variables in watermelon seedlings (Table 3). Highly significant interactions ($p < 0.001$) were observed for plant height (PH), Falker Chlorophyll Index (FCI), fresh mass (FM), total dry mass (TDM), total applied irrigation (TAI), water use efficiency (WUE), root length (RL), and stem diameter (SD), while number of leaves (NL) and dry matter content (DM%) also showed significant effects ($p = 0.010$ and $p = 0.022$, respectively). These results confirm that seedling performance depends on the interaction between the factors studied, justifying the joint analysis of the treatments.

Figure 1 shows the interaction between irrigation frequency (daily or every two days) and babassu mesocarp hydrogel doses on the vegetative growth parameters of watermelon seedlings: plant height (PH; Figure 1A), stem diameter (SD; Figure 1B), root length (RL; Figure 1C), and number of leaves (NL; Figure 1D), evaluated after 20 days of development. Overall, contrasting responses between irrigation regimes were observed for the evaluated growth parameters, consistent with the significant interaction effects identified by the analysis of variance, and demonstrating that hydrogel effectiveness is closely associated with irrigation management.

For plant height (PH; Figure 1A), under daily irrigation (24 h), hydrogel application did not fit any significant regression model ($p > 0.05$), indicating that the response of PH to hydrogel doses did not show a significant linear or quadratic regression pattern under frequent water supply. In contrast, under the 48-h irrigation interval, increasing hydrogel doses produced a significant decreasing linear response ($y = -0.040^{*}x + 8.38^{**}$; $R^2 = 0.894$; $p = 0.015$), leading to progressive reductions in plant height as polymer levels increased up to 40 g. This reduction suggests that, under prolonged irrigation intervals, higher hydrogel doses may have altered water availability dynamics within the substrate, potentially reducing the immediate availability of water to the developing root system and consequently limiting initial shoot elongation.

Table 3. Degrees of freedom (Df), mean squares (MS), *F* values, *p*-values, residual coefficients of variation (Residual CV), and irrigation-interval means obtained from the analysis of variance (ANOVA) for the effects of irrigation interval (II), hydrogel dose (HD), and their interaction (II × HD) on plant height (PH), Falker Chlorophyll Index (FCI), fresh mass (FM), total dry mass (TDM), total applied irrigation (TAI), water use efficiency (WUE), root length (RL), stem diameter (SD), number of leaves (NL), and dry matter content (DM%) of 'Crimson Sweet' watermelon seedlings. *p*-values < 0.05 indicate significant effects.

Variable	Source of Variation	Df	MS	F	*p*-value	Mean ± standard deviation		Residual CV (%)
						II (24-h)	II (48-h)	
PH	II	1	3.844	39.2	<0.001	8.20 ± 0.33	7.58 ± 0.67	3.97
	HD	4	0.654	6.7	<0.001			
	II × HD	4	1.594	16.3	<0.001			
	Residuals	30	0.098	-	-			
FCI	II	1	379.456	112.6	<0.001	34.78 ± 3.29	28.62 ± 2.62	5.79
	HD	4	29.120	8.6	<0.001			
	II × HD	4	41.656	12.4	<0.001			
	Residuals	30	3.370	-	-			
FM	II	1	0.0595984	81.6	<0.001	0.726 ± 0.052	0.649 ± 0.044	3.93
	HD	4	0.0072366	9.9	<0.001			
	II × HD	4	0.0115414	15.8	<0.001			
	Residuals	30	0.0007302	-	-			
TDM	II	1	0.0002704	14.8571	<0.001	0.076 ± 0.005	0.071 ± 0.007	5.83
	HD	4	0.0001786	9.8132	<0.001			
	II × HD	4	0.0001254	6.8901	<0.001			
	Residuals	30	0.0000182	-	-			
TAI	II	1	1343955.600	621.09095	<0.001	932.8 ± 324.0	566.2 ± 162.4	6.21
	HD	4	462673.000	213.81808	<0.001			
	II × HD	4	62670.600	28.96237	<0.001			
	Residuals	30	2163.863	-	-			
WUE	II	1	2.26576 × 10?8	836.3157	<0.001	0.00009 ± 0.00003	0.00014 ± 0.00005	4.67
	HD	4	9.94040 × 10??	366.9106	<0.001			
	II × HD	4	1.67560 × 10??	61.8482	<0.001			
	Residuals	30	2.709216 × 10?¹¹	-	-			
DM%	II	1	1.9892	10.3	0.003	10.45 ± 0.65	10.90 ± 0.47	4.13
	HD	4	1.9206	9.9	<0.001			
	II × HD	4	0.6484	3.3	0.022			
	Residuals	30	0.1940	-	-			
NL	II	1	0.0020	0.1	0.7899	3.50 ± 0.28	3.49 ± 0.29	4.72
	HD	4	0.5354	19.7	<0.001			
	II × HD	4	0.1090	4.0	0.0100			
	Residuals	30	0.0271	-	-			
RL	II	1	9.6040	6.3	0.018	20.44 ± 2.55	21.42 ± 3.46	5.89
	HD	4	53.0960	34.9	<0.001			
	II × HD	4	20.8840	13.8	<0.001			
	Residuals	30	1.5187	-	-			
SD	II	1	2.8730	122.7	<0.001	2.784 ± 0.176	2.248 ± 0.185	6.08
	HD	4	0.0730	3.1	0.029			
	II × HD	4	0.1878	8.0	<0.001			
	Residuals	30	0.0234	-	-			

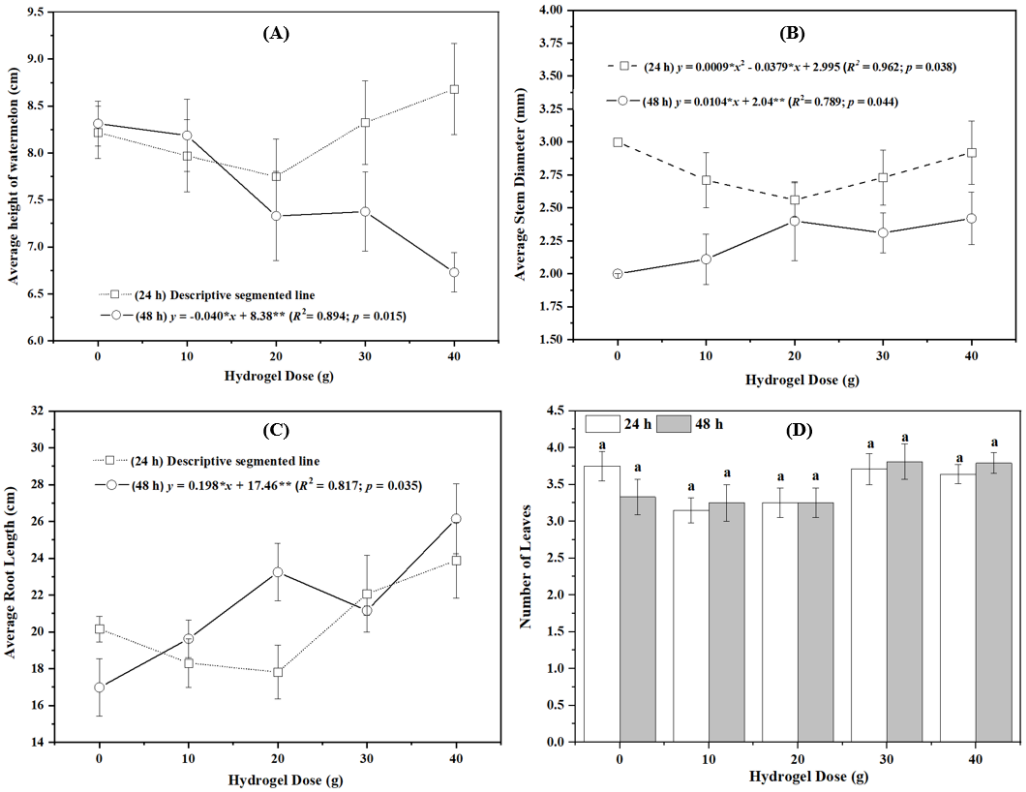


Figure 1. Vegetative growth parameters of watermelon (*Citrullus lanatus*) seedlings, 'Crimson Sweet' cultivar, as a function of babassu mesocarp hydrogel doses and irrigation intervals: plant height (PH; A), stem diameter (SD; B), root length (RL; C), and number of leaves (NL; D). Bars and data points represent treatment means (n = 4 replications), and vertical error bars indicate standard deviation. Regression significance: * $p < 0.05$; ** $p < 0.01$; In A and C, the 24h line is descriptive (mean comparisons in Table 2). For NL (D), means followed by the same lowercase letter are not significantly different between irrigation intervals within each hydrogel dose according to Tukey's test ($p < 0.05$).

A similar interaction pattern was observed for stem diameter (SD; Figure 1B). Under the daily irrigation regime, SD followed a significant quadratic model ($y = 0.0009*x^2 - 0.0379*x + 2.995$; $R^2 = 0.962$; $p = 0.038$), decreasing up to an estimated minimum point of 21.05 g before showing a slight recovery at higher doses. This temporary reduction in stem thickening under frequent watering combined with intermediate polymer levels may be associated with localized changes in substrate aeration. Conversely, under the 48-h irrigation interval, SD showed a significant linear increase ($y = 0.0104*x + 2.04**$; $R^2 = 0.789$; $p = 0.044$) with increasing hydrogel doses. This pattern indicates that, although daily irrigation may initially promote higher stem diameter values due to continuous water availability, hydrogel application under alternate-day irrigation may have partially mitigated fluctuations in substrate water availability, thereby favoring continuous stem thickening. A comparable response was reported by Silva et al. (2018), who observed that daily irrigation generally promotes larger stem diameters than longer irrigation intervals, unless adequate moisture is maintained using soil conditioners in soil-based cultivation systems.

For root length (RL; Figure 1C), seedlings also exhibited contrasting responses according to irrigation frequency. Under the daily irrigation regime, although minor numerical fluctuations occurred, the data did not fit any significant polynomial regression model ($p = 0.199$), indicating that the observed variations were better described by treatment means. This behavior may have occurred because continuous water supply reduced the necessity for extensive root exploration. Conversely, under the 48-h irrigation interval, RL fitted a significant linear model ($y = 0.198*x + 17.46**$; $R^2 = 0.817$; $p = 0.035$), showing a progressive increase with hydrogel addition up to the maximum tested dose (40 g). This increase under water-restricted intervals may be associated with hydrotropic responses combined with possible adjustments in biomass allocation, in which localized zones of greater water availability around the hydrogel particles may have stimulated greater root expansion to maximize water uptake under conditions of variable water availability. Similar results have been reviewed by Agbna and Zaidi (2025), who observed that hydrogels increase substrate water retention and promote greater root development and biomass accumulation under water stress. Likewise, Felippe et al. (2021) demonstrated substantial improvements in substrate available water storage following hydrogel application in *Eucalyptus dunnii*, emphasizing the importance of adequate polymer dosing.

Although the interaction between irrigation interval and hydrogel dose was statistically significant, regression analysis did not identify significant linear or quadratic models describing the response of NL, indicating that the interaction was expressed through differences among treatment combinations rather than a consistent linear or quadratic dose-response pattern. According to the mean separation test (Table 2), under daily irrigation (24 h), the 10 and 20 g hydrogel

doses resulted in significantly lower NL than the control, whereas the 30 and 40 g doses led to recovery in leaf production. Under the 48-h irrigation interval, the 30 and 40 g hydrogel doses resulted in significantly higher NL than the 10 and 20 g doses, whereas the control did not differ significantly from these intermediate doses. Thus, the significant interaction was associated with differences among treatment combinations across irrigation intervals, rather than with a consistent linear or quadratic response to increasing hydrogel doses. These results should therefore be interpreted with caution and do not indicate equality among hydrogel doses. Similar results were reported by Pereira et al. (2019), who found that intermediate hydrogel doses (1.5 g L^{-1}) promoted better vegetative growth in *Citrullus lanatus* seedlings. Although higher doses tended to reduce overall development in their study, increased leaf area was observed under specific shading conditions with 3.0 g L^{-1}, suggesting that environmental and substrate interactions can influence plant responses to hydrogel application.

Overall, the responses of PH, SD, RL, and NL indicate that hydrogel performance was strongly influenced by irrigation frequency. Under daily irrigation, intermediate hydrogel doses may have temporarily altered substrate physical conditions through increased water retention and reduced aeration, which may have affected shoot growth responses. Navroski et al. (2015) reported results consistent with this interpretation, showing that although hydrogel application improved the growth of *Eucalyptus dunnii* seedlings under reduced irrigation, excessive substrate moisture retention could promote saturation and reduce root oxygenation, negatively affecting plant development. Under the 48-h irrigation interval, increasing hydrogel doses were associated with greater root development and sustained vegetative growth, reinforcing the importance of integrating hydrogel dose with irrigation management to optimize early seedling development and improve water use efficiency.

Figure 2 illustrates the significant interaction between irrigation frequency and babassu mesocarp hydrogel doses on fresh mass (FM; Figure 2A), Falker Chlorophyll Index (FCI; Figure 2B), and total dry mass (TDM; Figure 2C) of 'Crimson Sweet' watermelon seedlings. In the absence of hydrogel (0 g), daily irrigation resulted in higher values for all evaluated parameters compared to irrigation every two days, reflecting the greater water availability under higher irrigation frequency.

Under the daily irrigation regime (24 h), seedling FM (Figure 2A) and TDM (Figure 2C) did not fit any significant polynomial regression model ($p > 0.05$), indicating that no consistent dose-dependent pattern of biomass accumulation was observed under frequent water supply. Conversely, under the restrictive 48-h irrigation interval, both parameters exhibited significant linear increases as hydrogel doses increased up to 40 g, described by the equations $y = 0.0026^{*}x + 0.615^{**}$ ($R^2 = 0.857$; $p = 0.024$) for FM and $y = 0.0004^{**}x + 0.0621^{**}$ ($R^2 = 0.957$; $p = 0.004$) for TDM. For the Falker Chlorophyll Index (FCI; Figure 2B), the treatment means were evaluated via mean separation tests.

The lack of additional biomass accumulation under frequent watering combined with high polymer levels suggests that when water supply is non-limiting, increasing hydrogel doses do not yield structural benefits, which may be associated with temporary changes in substrate aeration. At high hydrogel doses, the expansion of the hydrated polymer may occupy part of the substrate macropores, potentially restricting oxygen diffusion, impairing root respiration, and limiting nutrient uptake. Felippe et al. (2021) discussed that hydrogel incorporation can modify substrate physical properties, including aeration and water dynamics, providing a plausible explanation for the response observed here. Further studies evaluating substrate moisture retention curves, air-filled porosity, or oxygen diffusion rates would be necessary to confirm this mechanism. In agreement with these findings, Tripepi et al. (1991) reported reduced shoot biomass in *Betula pendula* grown in hydrogel-amended substrate under daily irrigation, suggesting that polymer expansion reduced pore space and impaired root-zone aeration.

Regarding the physiological responses, the Falker Chlorophyll Index (FCI; Figure 2B) exhibited dynamic variations between watering regimes depending on the applied hydrogel concentrations. Significant differences between irrigation intervals were restricted to the 10 g and 40 g doses, where the restrictive 48-h interval (gray bars) resulted in lower values (letter b) compared to the daily irrigation control (letter a). This initial reduction observed at the 10 g dose under water-restricted conditions suggests that low polymer concentrations may temporarily restrict water availability, a phenomenon possibly related to the high matric suction of the hydrogel, which intensifies leaf chlorophyll degradation compared to the control. However, at intermediate doses such as 20 and 30 g, the greater cumulative water storage capacity within the substrate overcame this localized water retention restriction, stabilizing the FCI values and showing no statistical differences between the 24-h and 48-h irrigation intervals. Finally, at the highest dose (40 g), the restrictive watering interval again compromised the chlorophyll index, suggesting that excessive polymer expansion might have triggered localized root stress or nutritional imbalances under prolonged alternate-day irrigation.

This preservation of chlorophyll was associated with significant linear increases in biomass under water deficit, as both FM (Figure 2A; $y = 0.0026^{*}x + 0.615^{**}$; $R^2 = 0.857$; $p = 0.024$) and TDM (Figure 2C; $y = 0.0004^{**}x + 0.0621^{**}$; $R^2 = 0.957$; $p = 0.004$) showed significant linear responses to increasing polymer levels. Although these TDM differences are narrow in absolute terms, ranging from approximately 0.063 to 0.079 g, the linear trend indicates that, under less frequent irrigation, the hydrogel contributed to maintaining moisture availability, reducing water stress, and supporting seedling development.

A comparative analysis across the entire Figure 2 shows that lower doses (0–10 g) were more effective under daily irrigation, while higher doses (30–40 g) produced similar or even superior biomass results under the 48-h interval. These findings highlight the potential of higher hydrogel doses to offset reduced irrigation frequency, ensuring adequate biomass accumulation under water-saving conditions. In *Eugenia myrcianthes*, during the initial phase of water deficit, hydrogel treatments contributed to the preservation of foliar chlorophyll content (SILVERIO et al., 2024). Furthermore, Diógenes et al. (2022) observed that the application of 6 g seedling^{-1} of hydrogel combined with irrigation intervals of approximately 3 days resulted in greater accumulation of dry biomass, photosynthetic pigments, and organic and inorganic solutes, supporting the potential of

appropriate hydrogel doses to improve seedling development under less frequent irrigation regimes. Ultimately, the combined evidence from Figure 2 indicates that hydrogel use tends to be more effective under less frequent irrigation, whereas under daily irrigation its effects on biomass accumulation were less pronounced and no consistent dose-dependent response was observed.

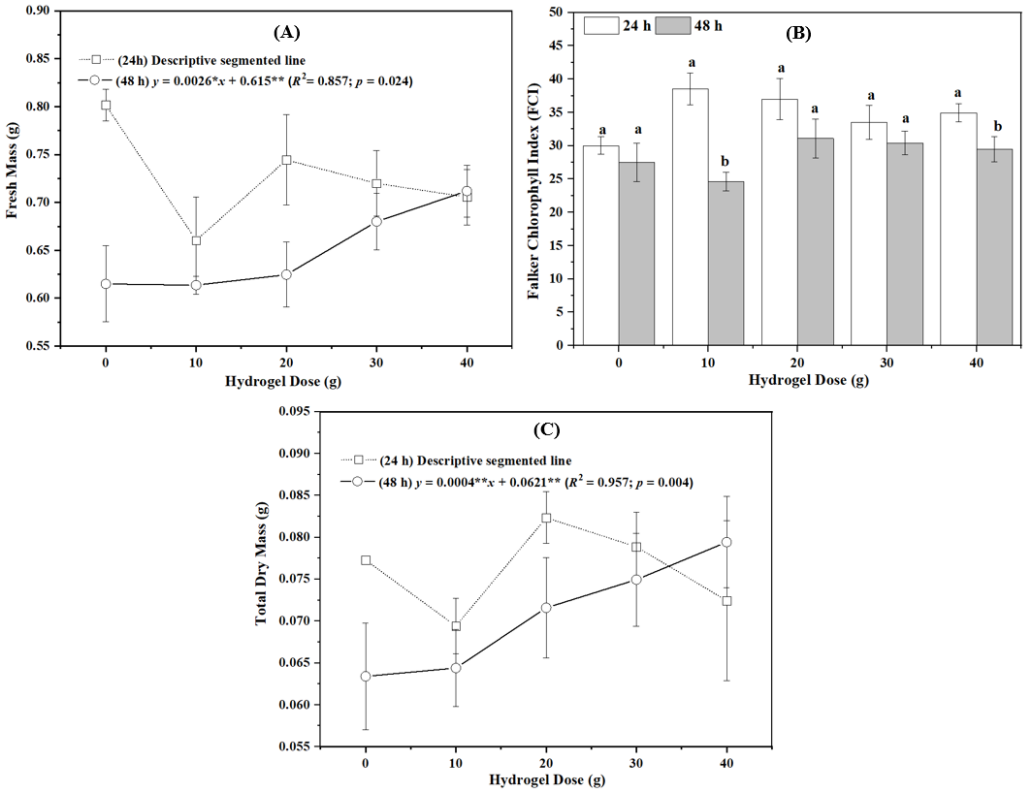


Figure 2. Fresh mass (FM; A), Falker Chlorophyll Index (FCI; B), and total dry mass (TDM; C) of watermelon (*Citrullus lanatus*) seedlings, 'Crimson Sweet' cultivar, subjected to different babassu mesocarp hydrogel doses and irrigation intervals. Bars and data points represent treatment means (n = 4 replications), and vertical error bars indicate standard deviation. Regression significance: * $p < 0.05$; ** $p < 0.01$; In A and C, the 24h line is descriptive (mean comparisons in Table 2). For FCI (B), means followed by the same lowercase letter are not significantly different between irrigation intervals within each hydrogel dose according to Tukey's test ($p < 0.05$).

Figure 3 shows the interaction between irrigation frequency (daily or every two days) and babassu mesocarp hydrogel doses on water relations and efficiency parameters of watermelon seedlings, including total applied irrigation (TAI; Figure 3A), water use efficiency (WUE; Figure 3B), and dry matter content (DM%; Figure 3C). The results indicate that hydrogel effectiveness was strongly influenced by irrigation frequency, dynamically modulating both water consumption patterns and the efficiency of water utilization during initial seedling development.

For total applied irrigation (TAI; Figure 3A), cumulative irrigation volume differed substantially between irrigation regimes during the experimental period. Under daily irrigation (24-h), cumulative irrigation volume ranged from approximately 1487 mL (equivalent to an irrigation depth of 247.29 mm) in the control treatment to 649 mL (107.94 mm) at the highest hydrogel dose. However, neither the linear nor the quadratic regression model was significant ($p > 0.05$), indicating that no significant linear or quadratic dose-response pattern was detected between hydrogel dose and cumulative irrigation volume under daily irrigation. In contrast, under the 48-h irrigation interval, TAI fitted a significant decreasing linear response ($y = -9.86^{**}x + 763.40^{**}$; $R^2 = 0.922$; $p = 0.009$). Cumulative irrigation volume decreased from approximately 816 mL (135.71 mm) in the control treatment to 400 mL (66.52 mm) at the highest hydrogel dose, corresponding to a reduction of approximately 51.0%. This linear decrease suggests that, under extended irrigation intervals, higher doses of babassu mesocarp hydrogel enhanced the availability of retained water in the substrate. Consequently, the cumulative irrigation volume required throughout the experimental period was reduced, while maintaining adequate moisture conditions for seedling development.

Importantly, because the water volume incorporated during polymer pre-hydration was accounted for in these cumulative values, the reductions observed reflect an actual decrease in replenishment requirements rather than an artifact associated with unaccounted initial moisture. These findings support the effectiveness of hydrogel application in reducing irrigation demand, exhibiting a highly pronounced and statistically significant effect under the prolonged 48-h irrigation interval, where irrigation events were less frequent. Conversely, under daily irrigation (24 h), no significant

regression model was identified for cumulative irrigation volume, indicating the absence of a significant linear or quadratic pattern as a function of hydrogel dose. Nevertheless, under the lower-input scenario represented by the 48-h interval, hydrogel incorporation contributed to more efficient water management, which may be particularly relevant under conditions of limited water availability. Similar results were reported by Abedi-Koupai, Sohrab, and Swarbrick (2008), who observed that hydrogel application at concentrations ranging from 2 to 8 g kg^{-1} increased available water by up to 3.2-fold in sandy loam soils compared with control soils without hydrogel. More recent studies have reinforced these findings, demonstrating that hydrogel incorporation improves substrate water availability and retention and contributes to extending irrigation intervals under containerized conditions (AVRELLA et al., 2021).

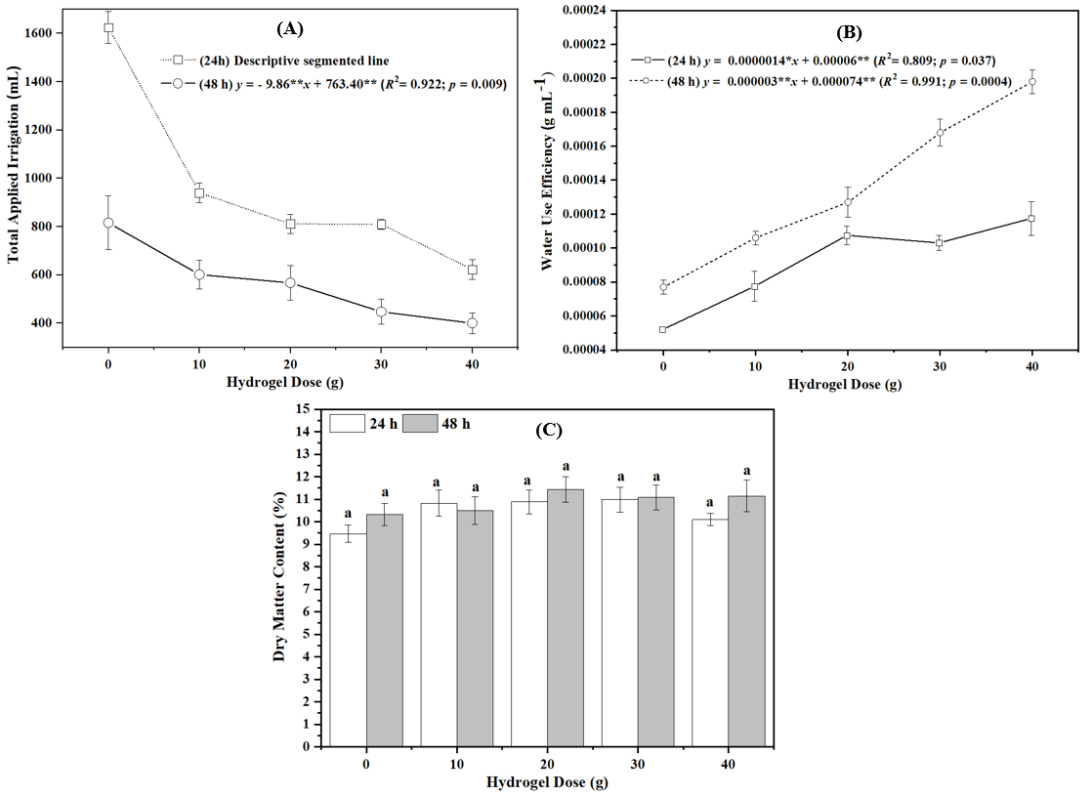


Figure 3. Water relations and efficiency parameters of watermelon (*Citrullus lanatus*) seedlings, 'Crimson Sweet' cultivar, as a function of babassu mesocarp hydrogel doses and irrigation intervals: total applied irrigation (TAI; A), water use efficiency (WUE; B), and dry matter content (DM%; C). Bars and data points represent treatment means (n = 4 replications), and vertical error bars indicate standard deviation. Regression significance: * $p < 0.05$; ** $p < 0.01$; In A, the 24h line is descriptive (mean comparisons in Table 2). For DM% (C), means followed by the same lowercase letter are not significantly different between irrigation intervals within each hydrogel dose according to Tukey's test ($p < 0.05$).

The response of water use efficiency (WUE; Figure 3B) also varied according to irrigation frequency. Under daily irrigation (24 h), WUE ranged from approximately 0.000052 g mL^{-1} in the control treatment to 0.000111 g mL^{-1} at the highest hydrogel dose (40 g), fitting a significant increasing linear response (y = 0.0000014*x + 0.00006**; R^2 = 0.809; p = 0.037). Although WUE increased with hydrogel addition, the magnitude of this response was lower compared with the 48-h irrigation interval. In contrast, under the 48-h irrigation interval, WUE fitted a significant increasing linear response (y = 0.000003**x + 0.000074**; R^2 = 0.991; p = 0.0004). Water use efficiency increased progressively from approximately 0.000077 g mL^{-1} in the control treatment to 0.000198 g mL^{-1} at the highest hydrogel dose, corresponding to an increase of approximately 157.1%. This linear response indicates that, under the 48-h irrigation interval, increasing babassu mesocarp hydrogel doses progressively enhanced water use efficiency, indicating a more efficient conversion of applied irrigation water into plant biomass.

The 48-h irrigation interval showed greater WUE values across all hydrogel doses, particularly at the highest concentrations, indicating that the combination of lower total water application and greater substrate water retention may improve water use efficiency during early seedling development. Agbna and Zaidi (2025) reviewed related findings, showing that hydrogel use increases water availability in soil-based cropping systems, allowing reductions in irrigation frequency and improving crop performance under water-limited conditions. Nevertheless, considering the short-term and containerized nature of the present study, these results should be interpreted as initial evidence, and further validation under commercial nursery or field conditions is recommended to refine large-scale

agricultural management strategies.

Although the interaction between irrigation interval and hydrogel dose was statistically significant (Table 3), regression analysis did not identify significant linear or quadratic models describing the response of dry matter content (DM%; Figure 3C). When the interaction was examined within each hydrogel dose, no significant differences were observed between the 24-h and 48-h irrigation intervals, as indicated by the identical lowercase letter ('a') assigned to the paired bars in Figure 3C. However, regarding the hydrogel factor under daily irrigation (24 h), the mean separation test (Table 2) showed higher DM% at 10, 20, and 30 g hydrogel doses compared with the control (9.47%), with the highest numerical value observed at 30 g (10.98%). These three doses did not differ statistically from each other, whereas DM% declined at 40 g (10.09%), which did not differ from the control. In contrast, under the 48-h irrigation interval, no significant linear or quadratic regression model was identified for the response of DM% to hydrogel doses. Therefore, the significant interaction in DM% reflected differences among specific treatment combinations rather than a consistent progressive response to increasing hydrogel doses. The absence of a significant dose-response model should be interpreted as a lack of a consistent dose-response pattern and not as evidence of equality among hydrogel doses. Similar responses were reported by Adjuik et al. (2022), who observed that moderate hydrogel application optimizes water retention and plant uptake, whereas excessive amounts may reduce saturated hydraulic conductivity and restrict oxygen diffusion in the root zone.

The combined responses of TAI, WUE, and DM% provide insights into the balance between water supply and plant water use during seedling establishment. Under the 48-h irrigation interval, increasing hydrogel doses reduced cumulative irrigation requirements and improved water use efficiency, while WUE also increased under the 24-h irrigation interval. These responses suggest that hydrogel incorporation may enhance water availability and water-use efficiency under reduced irrigation frequency, reinforcing its potential as a strategy for improving resource use during early seedling development.

CONCLUSION

The initial development and water use efficiency of 'Crimson Sweet' watermelon seedlings were influenced by the interaction between irrigation interval and babassu mesocarp hydrogel dose. Under daily irrigation (24 h), stem diameter showed a significant quadratic response to hydrogel dose, whereas the other growth and biomass accumulation parameters did not show significant linear or quadratic dose-response models. Conversely, with a 48-h irrigation interval, fresh mass, stem diameter, root length, and total dry mass (TDM) increased linearly with increasing hydrogel dose up to 40 g, while plant height decreased linearly. At this irrigation interval, increasing hydrogel doses reduced cumulative irrigation requirements, and water use efficiency increased linearly under both irrigation intervals. Under the conditions of this study (seedlings grown in 500-mL containers for 20 days under 25% shading), babassu mesocarp hydrogel showed potential to improve seedling performance, although further validation under commercial nursery and field conditions is recommended.

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