Comunicata Scientiae
Horticultural Journal

ORIGINAL ARTICLE
published: 13 July 2020
https://doi.org/10.14295/CS.v11i0.3339

Allometry and morphophysiology of papaya seedlings in a substrate with polymer under irrigation with saline water

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Abstract

The availability and quality of the irrigation water are among the limitations for the development of agriculture in the semiarid. Aiming at gathering information on these limitations, this work aimed to evaluate the association between a water-absorbing polymer and water salinity in irrigation frequencies, as well as container volumes on the allometric and morphophysiological indices of seedlings of the papaya (*Carica papaya*) cultivar 'Sunrise Solo'. The treatments were obtained from the combination between the water-absorbing polymer (0.0; 0.2; 0.6; 1.0, and; 1.2 g dm^{-3}), the electrical conductivity of the irrigation water (0.3; 1.1; 2.7; 4.3, and; 5.0 dS m^{-1}), and irrigation frequencies (daily and alternate), plus two additional treatments (0.75 and 1.30 dm^{3}) to study the effects of the container volume, distributed in a randomized block design. At 55 days after sowing, the following characteristics were evaluated: ratio between stem height and diameter; ratio between shoot and root dry matter; root density; leaf blade area; ratio between total leaf area and root dry mass; specific leaf area; leaf area ratio; leaf mass ratio; and Dickson quality index. The allometric and morphophysiological indices were damaged by the increase of water electrical conductivity and favored by the application of the polymer and a higher irrigation frequency. In the production of papaya seedlings, a daily irrigation frequency must be prioritized, using containers of 0.75 or 1.30 dm^{-3}, water with electrical conductivity up to 2.6 and 1.9 dS m^{-1} when irrigated daily or in alternate days, respectively, and 0.6 g dm^{-3} of polymer.

Keywords: *Carica papaya* L., container, irrigation shift, salinity, water-absorbing polymer

Introduction

The papaya crop (*Carica papaya* L.) belongs to the family Caricaceae and is one of the main fruit species produced in tropical and subtropical regions, with India, Brazil, and Mexico ranking as the main producers, jointly summing 13.29 thousand tons in 2018, with participations of 45, 8, and 8 %, respectively (Faostat, 2018).

In the Brazilian Northeast, the main obstacles to agricultural production are the low rainfall associated with spacetime irregularity and the high concentration of salts in the water. In papaya cultivation, salt excess damages seedling formation (Cavalcante et al., 2010; Sá et al., 2013a, b; Santos et al., 2015), yield, and quality of fruits, being then essential to use quality seedlings for the formation of an orchard (Bezerra et al., 2014). One index used to infer the quality of seedlings is the Dickson quality index (Dickson, 1960), based on the biometric relationships of the shoot and root parts, resulting from their physiological interactions reflected on plant architecture (Bezerra et al., 2019).

Seedling production with saline water considerably increases the concentration of salts (Sá et al., 2013b; Bezerra et al., 2014; Silva et al., 2018a) and toxic ions in the substrate, such as sodium (Sá et al., 2015). In a saline environment, there is less absorption of water by plant roots, besides increasing the absorption and accumulation of toxic ions, promoting a nutritional imbalance (Taiz et al., 2017). These stress conditions can change the dry matter allocation pattern (Sá et al., 2013a, b; Sá et al., 2015; Santos et al., 2015; Moura et al., 2020) and, consequently, the allometric and morphophysiological indices of the seedlings. In this manner, measures that allow the use of waters with high saline content or residual waters (Cardoso et al., 2020) should be made possible to allow the employment of this often-limiting resource.

Received: 27 March 2020
Accepted: 13 May 2020

The adequation of container volume, irrigation frequency, and use of water-absorbing polymers are factors that can provide improvements in the formation and quality of seedlings (Carvalho et al., 2013; Silva et al., 2018a, b), besides mitigating the effects of the electrical conductivity of the irrigation water. In the last few years, several studies have highlighted the use of polymers, aiming, in most cases, at solving problems related to the regularity of soil water availability, and even at reducing the irrigation frequency (Fernandes et al., 2015; Navroski et al., 2015).

Water-absorbing polymers, when dry, present a granular and brittle shape and become soft and elastic when hydrated, and can raise in up to four times the diameter of the pores that store water, as well as reduce nutrient leaching (Carvalho et al., 2013; Fagundes et al., 2014, 2015). Besides improving soil conditioning, they also optimize its physical-hydric properties (Fagundes et al., 2015), considering that the reduction in water availability can negatively interfere with the physiology of papaya plants (Lima et al., 2016).

In this manner, this research aimed to evaluate the effects of the association between saline water and water-absorbing polymer in irrigation frequencies and container volumes on the allometric and morphophysiological indices of Hawaii papaya seedlings.

Material and Methods

The experiment was developed in a plant nursery (6° 58’ 10.9” South, 35° 42’ 59.1” West, and 536 m of elevation) at the Department of Soils and Rural Engineering of the Center of Agricultural Sciences of the Federal University of Paraíba (CCA/UFPB), municipality of Areia, State of Paraíba, Brazil.

The treatments were organized according to the following model: $[(2^2 + 2 \times 2 + 1) \times 2] + 2$ (Table 1), with the doses of the Hydroplan-EB/HyA polymer (0.0; 0.2; 0.6; 1.0, and 1.2 g dm^{-3}) and electrical conductivities of the irrigation water (0.3; 1.1; 2.7; 4.3, and 5.0 dS m^{-1}) arranged according to the Box-Wilson central composite design matrix, $2^2 + 2 \times 2 + 1$ (Montgomery, 2013), and combined with two irrigation frequencies (daily and alternate), plus two additional treatments (0.75 and 1.30 dm^3) to study the effects of the container volumes. The treatments were distributed in four randomized blocks, and the experimental unit was constituted by four containers, each containing one seedling.

Table 1. Arrangement between the factors (HyA – polymer; ECw – electrical conductivity of the irrigation water; FI – irrigation frequency, and CtV – container volume) used in the experiment.

Treatment[1]	Levels[2]		Doses/Concentrations		FI	CtV (dm^3)
	HyA	ECw	HyA (g dm^{-3})	ECw (dS m^{-1})		
1	-1	-1	0.2	1.1	Daily	0.75
2	-1	1	0.2	4.3	Daily	0.75
3	1	-1	1.0	1.1	Daily	0.75
4	1	1	1.0	4.3	Daily	0.75
5	$-\alpha$[3]	0	0.0	2.7	Daily	0.75
6	α	0	1.2	2.7	Daily	0.75
7	0	$-\alpha$	0.6	0.3	Daily	0.75
8	0	α	0.6	5.0	Daily	0.75
9	0	0	0.6	2.7	Daily	0.75
10	-1	-1	0.2	1.1	Alternate	0.75
11	-1	1	0.2	4.3	Alternate	0.75
12	1	-1	1.0	1.1	Alternate	0.75
13	1	1	1.0	4.3	Alternate	0.75
14	$-\alpha$	0	0.0	2.7	Alternate	0.75
15	α	0	1.2	2.7	Alternate	0.75
16	0	$-\alpha$	0.6	0.3	Alternate	0.75
17	0	α	0.6	5.0	Alternate	0.75
18	0	0	0.6	2.7	Alternate	0.75
19	0	0	0.6	2.7	Daily	1.30
20	0	0	0.6	2.7	Alternate	1.30

[1]Number of treatments for each arrangement between polymer doses and electrical conductivity of the irrigation water = $2^k + 2k + 1$ (k = 2, number of factors) ∴ $2^2 + 2 \times 2 + 1 = 9$; [2]Contrasts established according to the Box-Wilson central matrix; [3]$\alpha = \sqrt{k}$.

The substrate consisted of the mixture of a Red-Yellow Latosol, washed sand, and bovine manure, in the respective ratio of 3:2:1. The Latosol proportion was collected from the 0-20 cm layer depth at the Experimental Station *Chã do Jardim*, municipality of Areia, State of Paraíba. The bovine manure was obtained in a stable in the rural area of the region, being previously cured and air-dried in the shade. After the collection of the substrate components, the material was subjected to air-drying in the shade, passed through a 4 mm mesh sieve, and homogenized. In the end, one composite sample was taken for the characterization of the chemical (fertility and salinity) and physical attributes of the substrate (Table 2).

Table 2. Chemical (fertility and salinity) and physical attributes of the substrate used for the production of papaya seedlings

Chemical attributes				Physical attributes[3]	
Fertility[1]		Salinity[2]			
pH (1:2,5 H_2O)	5.90	pH	5.90	Sand (g kg^{-1})	686.7
EC (dS m^{-1})	0.46	ECse (dS m^{-1})	1.97	Silt (g kg^{-1})	181.7
Ca^{2+} ($cmol_c$ dm^{-3})	1.74	Ca^{2+} ($mmol_c$ L^{-1})	4.62	Clay (g kg^{-1})	131.6
Mg^{2+} ($cmol_c$ dm^{-3})	1.28	Mg^{2+} ($mmol_c$ L^{-1})	8.88	Sd (kg dm^{-3})	1.35
K^+ ($cmol_c$ dm^{-3})	0.88	K^+ ($mmol_c$ L^{-1})	5.46	Pd (kg dm^{-3})	2.64
Al^{3+} ($cmol_c$ dm^{-3})	0.50	Na^+ ($mmol_c$ L^{-1})	5.13	TP (m^3 m^{-3})	48.86
Na^+ ($cmol_c$ dm^{-3})	0.23	CO_3^{2-} ($mmol_c$ L^{-1})	0.00	Moisture (%)	0.94
H^++Al^{3+} ($cmol_c$ dm^{-3})	9.47	HCO_3^- ($mmol_c$ L^{-1})	2.80	0.033 MPa	15.81
SB ($cmol_c$ dm^{-3})	4.13	SO_4^- ($mmol_c$ L^{-1})	Pres.	1.500 MPa	8.22
CEC ($cmol_c$ dm^{-3})	13.60	Cl^- ($mmol_c$ L^{-1})	15.25		
ESP (%)	1.69	SAR ($mmol_c$ L^{-1})$^{-0,5}$	1.98		
V (%)	30.37				
P (mg dm^{-3})	45.00				
O.M. (g kg^{-1})	24.30				

[1]EC – electrical conductivity of the soil-water suspension (1:2.5 H_2O); SB (sum of exchangeable bases) = Ca^{2+} + Mg^{2+}+ K^+ + Na^+; CEC (cation exchange capacity) = SB + (H^++Al^{3+}); ESP (exchangeable sodium percentage) = (Na^+/CEC) × 100; V (base saturation) = (SB/CEC) × 100; O.M. (organic matter); [2]ECse (electrical conductivity of soil saturation extract); SAR (sodium adsorption ratio) = $Na^+/\sqrt{((Ca^{2+} + Mg^{2+})/2)}$; [3]Sd (soil density); Pd (particle density), TP (total porosity).

The fertilization was formulated based on the fertility analysis of the substrate, increasing the levels of phosphorus and nitrogen to 300 and 100 mg kg^{-1}, respectively. The Hidroplan®-EB/HyA polymer was hydrated in the proportion of 1 g per 49 mL of distilled water, and incorporated to the substrate according to the evaluated doses (Table 1). After the filling, the containers were irrigated in order to accommodate the particles of the substrate for sowing.

Seeds of the papaya (*Carica papaya* L.) cultivar 'Sunrise Solo' (Soil group) were used for sowing. Three seeds were sown per container at a 1.5 cm depth, and after emerging, the seedlings were thinned, keeping only one plant per container. Daily irrigation was performed to keep the substrate always close to field capacity, whereas the irrigation in alternate days was performed seven days after thinning by applying a volume corresponding to 70 % of the total used in daily irrigation. The preparation of the irrigation water was performed through the addition, in supply water (0.3 dS m^{-1}), of sodium (Na^+), calcium (Ca^{2+}), and magnesium ions (Mg^{2+}), in a 5:2:1 ratio based on mass (Silva Júnior et al., 1999), respectively, associated to chloride (Cl^-). The final concentrations of the salts in the irrigation waters were determined as a function of the electrical conductivities, measured with a portable conductivity meter.

At 55 days after sowing, the following variables were determined: ratio between stem height and diameter (H/C), with the height comprising the distance between the base of the plant and the apical bud, and the diameter measured with a pachymeter at the base of the plant; ratio between shoot dry matter and root dry matter (SDM/RDM); root density (RD), ratio between root dry matter and mass of the substrate; leaf blade area (LBA), through the pixels of the leaf images obtained by photography, taking as a reference a 5 x 5 cm area (25 cm^2) inserted in the images, with the processing of the data being performed in the SigmaScan® Pro software, version 5.0.; ratio between the total leaf area (number of leaves x leaf blade area) and root dry matter (LA/RDM); specific leaf area (SLA); leaf area ratio (LAR); and leaf mass ratio (LMR), according to equations 1, 2, and 3, respectively (Hunt, 1990), and Dickson quality index (DQI), according to equation 4 (Dickson et al., 1960).

$$SLA = \frac{Leaf\ area\ (cm^2)}{Leaf\ dry\ matter\ (g)} \quad \text{Equation 1}$$

$$LAR = \frac{Leaf\ area(cm^2)}{Total\ dry\ matter\ (g)} \quad \text{Equation 2}$$

$$LMR = \frac{Leaf\ dry\ matter\ (g)}{Mass\ of total\ dry\ matter\ (g)} \quad \text{Equation 3}$$

$$DQI = \frac{Total\ dry\ matter\ (g)}{\frac{Height\ (cm)}{Stem\ diameter\ (mm)} + \frac{Shoot\ dry\ matter\ (g)}{Root\ dry\ matter\ (g)}} \quad \text{Equation 4}$$

The data were subjected to normality analysis by the Kolmogorov-Smirnov test, being transformed into log (y + 10) when not adjusted to the Gauss distribution. Afterward, the analysis of variance was performed. The quantitative effects of the polymer and the electrical conductivity of the water were adjusted to the polynomial regression using the F-test ($p \leq 0.10$) to verify the significance of the orthogonal effects. The responses for the container volumes were analyzed by contrasts, using the F-test ($p \leq 0.05$) to determine the significance of the effects. The analyses were performed in the SAS® University Edition software.

Results

The effects of irrigation frequency, container volume, and the trends as a function of the polymer doses and electrical conductivity of the irrigation water on the allometric parameters of papaya seedlings can be seen in Table 3. It is highlighted that the irrigation frequency affected the relationship between stem height and diameter, as well as the leaf blade area, and interacted with the effects of the saline water and the polymer (BCC) on root density and leaf blade area, and for that reason, the adjustments as a function of quantitative factors were performed under each irrigation frequency.

The relationship between stem height and diameter in papaya seedlings differed regarding the irrigation frequency, and the trends as a function of the electrical conductivity of the irrigation water and the polymer were independent in relation to each other (Table 3). The daily irrigation provided, on average, 2.32 cm mm^{-1}, reducing by 9 % in the seedlings irrigated in alternate days (Figure 1). The reduction in the ratio between stem height and diameter with the increase in the electrical conductivity of the water was also evidenced, being more intense under daily irrigation (Figure 1A) than in alternate days (Figure 1B), with rates of 0.1076 and 0.0913 cm mm^{-1}, respectively, per unitary increment in the electrical conductivity of the water. Meanwhile, the polymer raised the respective ratio by 0.2207 cm mm^{-1} when used under daily irrigation (Figure 1A), and by 0.2895 cm mm^{-1} when under an alternate irrigation frequency (Figure 1B). It was also verified that the volumes of the containers did not exert effects on the relationship between stem height and diameter of papaya seedlings (Table 3).

Table 3. Summary of the analysis of variance, regression, and contrasts for the variables of ratio between stem height and diameter (H/D), between shoot and root dry mass (SDM/RDM), root density (RD), and leaf blade area (LBA) of the Hawaii papaya at 55 days after sowing under the factors of electrical conductivity of the irrigation water (ECw), polymer (P), irrigation frequency (IF), and container volume.

Variation source	GL	Mean Square			
		H/D	SDM/RDM[1♦]	RD[1♦]	LBA[1♦]
Block	3	0.1023^{ns}	0.0022^{ns}	0.0012^{ns}	3.5324^{ns}
Treatament	(19)	0.1824**	0.0035**	0.1447**	38.7578**
Frequency (IF)	1	0.7023**	0.0043^{ns}	0.0370^{ns}	60.4714**
BCC[2]	8	0.3225**	0.0062**	0.3176**	67.7853**
BCC x IF	8	0.0213^{ns}	0.0017^{ns}	0.0678*	23.3364**
Residual	56	0.0596	0.0015	0.0192	2.8029
CV (%)		11.00	3.44	0.43	3.50
Mean		2.22 cm mm^{-1}	2.90 g g^{-1}	0.24 g g^{-1}	23.4 cm^2
		Regression[3]			
P-L	1	-	0.0353**	-	-
P-Q	1	-	0.0031^{ns}	-	-
ECw-L	1	-	0.0004^{ns}	-	-
ECw-Q	1	-	0.0052°	-	-
P-L x ECw-L	1	-	0.0000^{ns}	-	-
		Regression[4] / Daily irrigation			
P-L	1	0.8596**	-	0.8662**	330.2978**
P-Q	1	0.0978^{ns}	-	0.1207*	0.5246^{ns}
ECw-L	1	0.2650*	-	0.0047^{ns}	0.0528^{ns}
ECw-Q	1	0.1382^{ns}	-	0.1419**	1.7075^{ns}
P-L x ECw-L	1	0.0101^{ns}	-	0.0387^{ns}	0.9132^{ns}
		Regression[4] / Irrigation in alternate days			
P-L	1	0.7094**	-	1.1492**	169.5135**
P-Q	1	0.0169^{ns}	-	0.1672**	0.8321^{ns}
ECw-L	1	0.4559**	-	0.0203^{ns}	0.0032^{ns}
ECw-Q	1	0.0092^{ns}	-	0.1215*	7.5787^{ns}
P-L x ECw-L	1	0.0711^{ns}	-	0.0006^{ns}	1.3755^{ns}
		Contrasts[5]			
Y1	1	0.0137^{ns}	0.0015^{ns}	0.0131^{ns}	29.4994**
Y2	1	0.0051^{ns}	0.0015^{ns}	0.0229^{ns}	9.7304^{ns}

[1]Data transformed into log (y+10); [2]Combinations between the electrical conductivity of the irrigation water and polymer doses, using the Box-Wilson central composite design (BCC); [3]Without effect or interaction with the irrigation frequency; [4]Considering the effect and/or interaction with the irrigation frequency; [5]Effect of the container volume (0.75 x 1.30 dm^3) in the daily (Y1) and alternate (Y2) irrigation frequencies; ♦Mean Square Values multiplied by 1,000; ns, °, * and **: not significant and significant at 10, 5, and 1% of probability by the F-test, respectively.

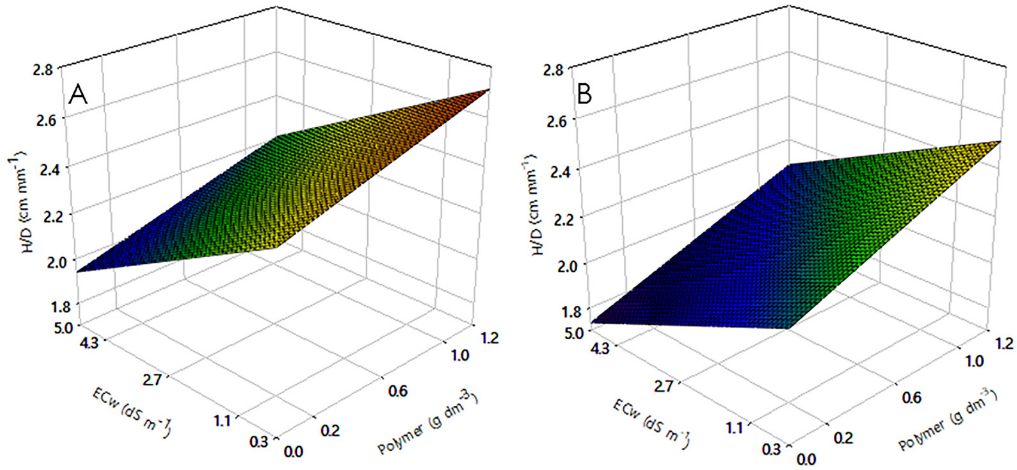

Figure 1. Ratio between stem height and diameter (H/C) of Hawaii papaya seedlings, at 55 days after sowing as a function of polymer (P) doses in the substrate and electrical conductivity of the irrigation water (ECw) under daily (A) and alternate irrigation frequencies (B). ŷ (A) = 2.48 + 0.2207*P – 0.1076**ECw, R^2 = 0.8712; ŷ (B) = 2.19 + 0.2895**P – 0.0913**ECw, R^2 = 0.8791. * and **: significant at 5 and 1% of probability by the F-test, respectively.

The allocation of dry matter in the shoot part and the root system of the papaya seedlings was not influenced by the irrigation frequency, as well no effects were registered for the container volumes (Table 3). Regarding the water electrical conductivity and the use of polymer, the effects were isolated and distinct (Figure 2). The unitary increase of the electrical conductivity of the water used in irrigation increased by 0.4458 g g^{-1} the ratio between the dry biomass of shoot and root parts, increasing, on average, from 2.37 to 4.47 g g^{-1} under 0.3 and 5.0 dS m^{-1}, respectively. On the other hand, the increase in the polymer content in the substrate reduced this ratio down to the value of 1.57 g g^{-1}, obtained at the 0,7 g dm^{-3} dose, representing a reduction of 34% in relation to the absence of the polymer. However, the results obtained in the concentrations between 0.7 and 1.2 g dm^{-3} evidenced an increase of the respective ratio to 2.11 g g^{-1}.

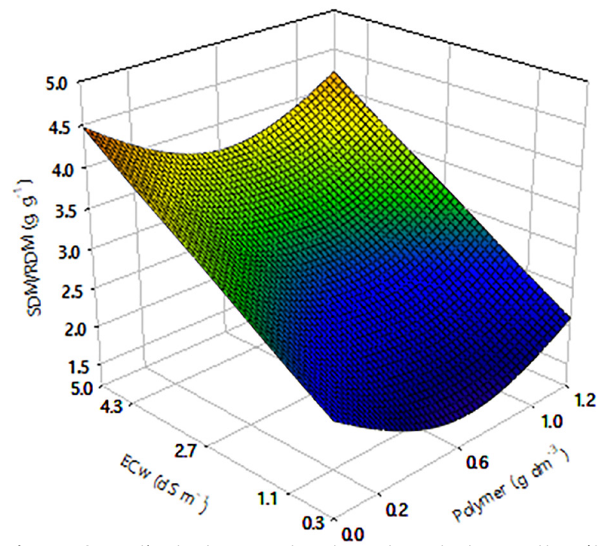

Figure 2. Ratio between shoot and root dry matter (SDM/RDM) in Hawaii papaya seedlings at 55 days after sowing as a function of the polymer doses (P) in the substrate and the electrical conductivity of the irrigation water (ECw). ŷ = 2.24 – 2.4559P + 1.8641°P^2 + 0.4458**ECw, R^2 = 0.8384, ° and **: significant at 10 and 1% of probability by the F-test, respectively.

The root density responses of the papaya seedlings to the electrical conductivity of the irrigation water and the polymer, although independent in relation to each other, were influenced by the irrigation frequency (Table 3). Under daily irrigation, the increase in the electrical conductivity reduced the root density from 0.45 to 0.08 g g^{-1}, a loss of 82 % among the seedlings irrigated with water of 0.3 and 5.0 dS m^{-1}, respectively (Figure 3A). Meanwhile, the increase in the polymer dose from 0.0 to 0.6 g dm^{-3} increased root density from 0.44 to 0.52 g g^{-1}, an increase of 18 %, although it was reduced to 0.42 g g^{-1} at the highest polymer dose. In the seedlings irrigated in alternate days, the reduction was from 0.44 to 0.03 g g^{-1}, a loss of 93 %, from the lowest to the highest conductivity of the irrigation water (Figure 3B). The polymer increased root density, with the highest increase at the dose of 0.8 g dm^{-3}, an 18 % gain compared to the 0.44 g g^{-1} obtained without the application of the polymer. The container volumes did not affect this variable (Table 3).

The irrigation frequency exerted an effect on the size of the leaves, per se, and when associated with the electrical conductivity of the irrigation water (Table 3). The size of the papaya leaves reduced from 26.1, under daily irrigation, to 20.7 cm^2 with an alternate irrigation shift, a loss of 21 % (Figure 4A). The increase in the electrical conductivity of the irrigation water also reduced the size of the leaf (Figure 2B). Under daily irrigation, the reduction was equivalent to 4.9 cm^2 per leaf, changing from 388 to 14.2 cm^2 under the water electrical conductivity of 0.3 and 5.0 dS m^{-1}, respectively. With an alternate frequency, the reduction was equivalent to 3.2 cm^2 per leaf, changing from 28.0 to 12.7 cm^2 under the water electrical conductivity of 0.3 and 5.0 dS m^{-1}, respectively. Under daily irrigation, it was observed that the larger volume containers provided a gain of 9.1 cm^2 (36 %) in the size of the leaf compared to the previous container, with a mean of 25.2 cm^2 (Figure 1C). In the alternate irrigation shift, no effect of the size of the container was observed for this variable.

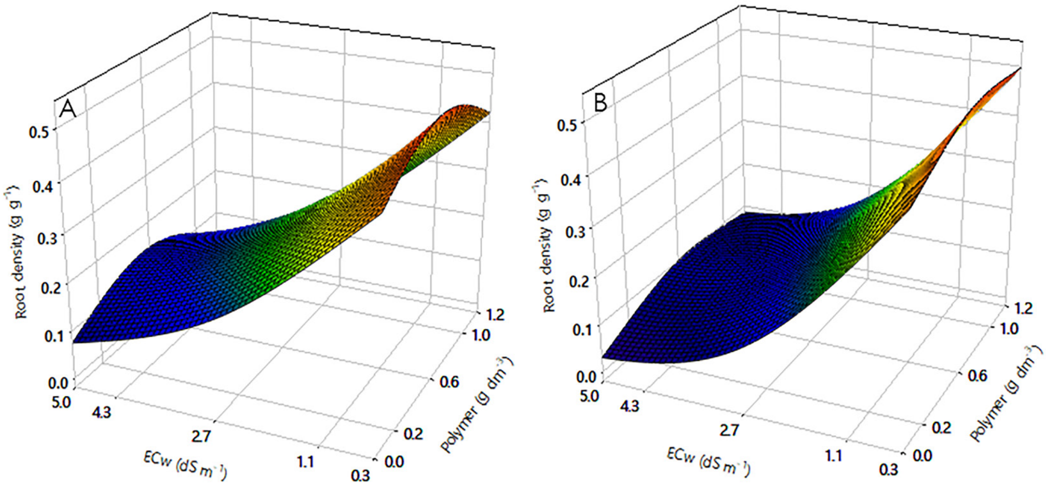

Figure 3. Root density of Hawaii papaya seedlings at 55 days after sowing as a function of polymer doses (P) in the substrate and the electrical conductivity of the irrigation water (ECw) under daily (A) and alternate irrigation frequencies (B). $\hat{y}$ (A) = 0.49 + 0.2530P – 0.2299**P^2 – 0.1459**ECw + 0.0126*ECw^2, R^2 = 0.8213; $\hat{y}$ (B) = 0.50 + 0.1856P – 0.1168*P^2 – 0.1964**ECw + 0.0205**ECw^2, R^2 = 0.9844. * and **: significant at 5 and 1% of probability by the F-test, respectively.

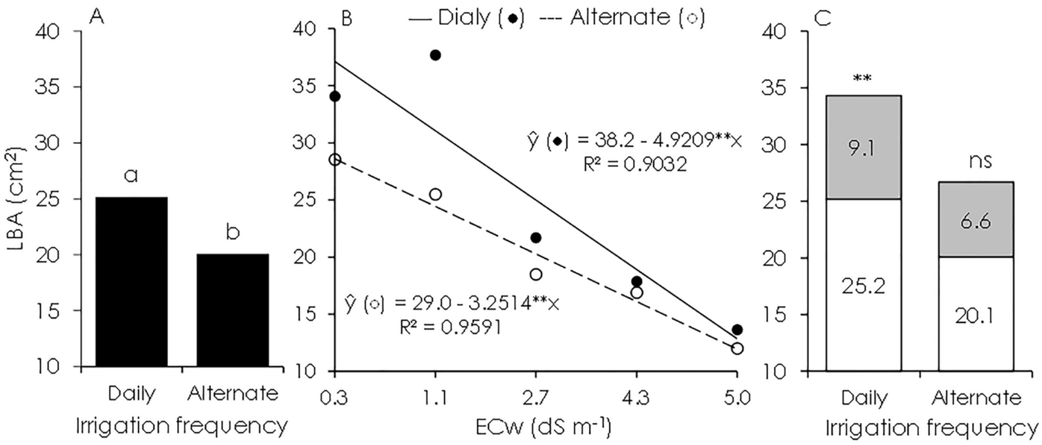

Figure 4. Leaf blade area in Hawaii papaya seedlings at 55 days after sowing, regarding the irrigation frequency (A), electrical conductivity of the irrigation water (B), and effects of container volumes (C). Means followed by the same letter do not differ from each other by the F-test ($p \leq 0.05$); ns and **: not significant and significant at a 1% level of probability by the F-test, respectively; ■ Real effect: smallest container (0.75 dm^3) – largest container (1.30 dm^3).

The effects of irrigation frequency, container volume, and trends as a function of the polymer doses and electrical conductivity of the irrigation water on the morphophysiological indices of papaya seedlings are indicated in Table 4. It is observed that only for the variables of specific leaf area and Dickson quality index was the interaction between irrigation frequency and effects of saline water and polymer (BCC) significant, with the adjustments as a function of the quantitative factors being performed at each irrigation shift.

The ratio between the total leaf area and root dry mass (LA/RDM) of papaya seedlings was only influenced by the isolated effects of the electrical conductivity of the irrigation water and the polymer (Table 4). It was observed that the increase of the water electrical conductivity from 0.3 to 5.0 dS m^{-1} increased by 152 % the LS/RDM ratio, with respective values of 643.6 and 1619.7 cm g^{-1} (Figure 5). The increase of the polymer in the substrate, from 0.0 to 0.7 g dm^{-3}, reduced this ratio by 49 %, with respective means of 643.6 and 331.2 cm g^{-1}, increasing by 64 % when changing from 0.7 to 1.2 g dm^{-3} of the polymer.

Table 4. Summary of the analysis of variance, regression, and contrasts for the variables of ratio between the total leaf area and root dry matter (LA/RDM), specific leaf area (SLA), leaf area ratio (LAR), leaf mass ratio (LMR), and Dickson quality index (DQI) of the Hawaii papaya at 55 days after sowing under the factors of electrical conductivity of the irrigation water (ECw), polymer (P), irrigation frequency (IF), and container volume.

Source of variation	GL	Mean Square				
		LA/RDM[1]♦	SLA[1]♦	LAR♦	LMR[1]♦	DQI[1]♦
Block	3	15.6739^{ns}	22.7642^{ns}	5,534.6167^{ns}	0.0186^{ns}	0.0013^{ns}
Treatment	(19)	131.4564**	38.7366**	10,281.4661**	0.0208^{ns}	0.0673**
Frequency (IF)	1	39.8223^{ns}	0.3217^{ns}	136.9610^{ns}	0.0202^{ns}	0.0105^{ns}
BCC[2]	8	266.8408**	67.0635**	21,309.4435**	0.0191^{ns}	0.1262**
BCC x IF	8	39.0080^{ns}	21.5740*	2,247.4245^{ns}	0.0309^{ns}	0.0250**
Residual	56	38.8127	10.0135	3,046.7408	0.0165	0.0071
CV (%)		6.80	3.90	25.08	0.40	0.26
Mean		903.43 cm^2 g^{-1}	375.8 cm^2 g^{-1}	220.1 cm^2 g^{-1}	0.60 g g^{-1}	0.18
		Regression[3]				
P-L	1	6.6445^{ns}	-	182.4336^{ns}	0.0101^{ns}	-
P-Q	1	251.1019*	-	11,401.1484°	0.0194^{ns}	-
ECw-L	1	1,617.4845**	-	130,155.4402**	0.0347^{ns}	-
ECw-Q	1	232.1329*	-	7,538.5005^{ns}	0.0599°	-
P-L x ECw-L	1	17.3292^{ns}	-	2,838.6189^{ns}	0.0020^{ns}	-
		Regression[4] / Daily irrigation frequency				
P-L	1	-	18.4845^{ns}	-	-	0.0016^{ns}
P-Q	1	-	5.0473^{ns}	-	-	0.0441*
ECw-L	1	-	159.6791**	-	-	0.3711**
ECw-Q	1	-	0.4683^{ns}	-	-	0.0279°
P-L x ECw-L	1	-	16.3402^{ns}	-	-	0.0058^{ns}
		Regression[4] / Irrigation frequency in alternate days				
P-L	1	-	2.1024^{ns}	-	-	0.0036^{ns}
P-Q	1	-	19.8451^{ns}	-	-	0.0430*
ECw-L	1	-	246.9053**	-	-	0.4609**
ECw-Q	1	-	5.3135^{ns}	-	-	0.0490*
P-L x ECw-L	1	-	32.3448^{ns}	-	-	0.0002^{ns}
		Contrasts[5]				
Y1	1	13.4970^{ns}	0.3063^{ns}	168.7709^{ns}	0.0003^{ns}	0.0137^{ns}
Y2	1	82.2633^{ns}	7.7481^{ns}	4,096.0737^{ns}	0.0103^{ns}	0.1311**

[1]Data transformed into log (y+10); [2]Combinations between the electrical conductivity of the irrigation water and polymer doses, using the Box-Wilson central composite design (BCC); [3]Without effect or interaction with the irrigation frequency; [4]Considering the effect and/or interaction with the irrigation frequency; [5]Effect of container volume (0.75 x 1.30 dm^3) on daily (Y1) and alternate (Y2) irrigation frequencies; ♦Mean Square values multiplied by 1,000; ^{ns}, °, * and **: not significant and significant at 10, 5, and 1% of probability by the F-test, respectively.

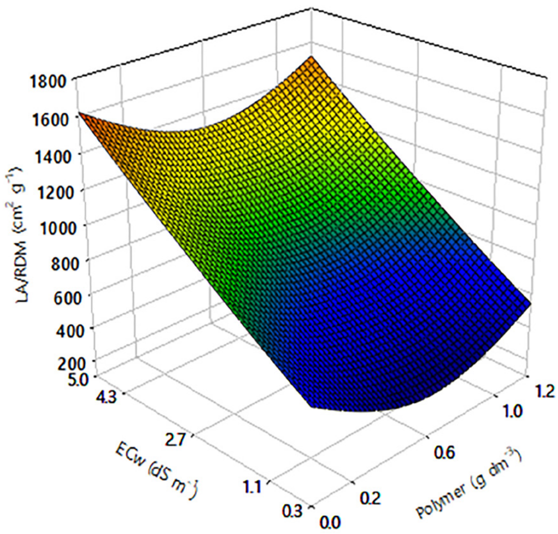

Figure 5. Ratio between total leaf area and dry root matter (LA/RDM) in Hawaii papaya seedlings at 55 days after sowing as a function of polymer doses (P) in the substrate and electrical conductivity of the irrigation water (ECw). $\hat{y}$ = 588.23 – 953.3020P + 724.2445*P^2 + 183.3160**ECw + 4.5974*ECw^2, R^2 = 0.9310. * and **: significant at 5 and 1% of probability by the F-test, respectively.

The specific leaf area (SLA) of the papaya seedlings responded only to the effects of the electrical conductivity of the irrigation water, with the effects associated with the irrigation frequency (Table 4). Under a daily irrigation frequency, the specific leaf area increased by 44.53 cm^2 g^{-1}, or 16 %, per increase of each 1.0 dS m^{-1} of water, whereas under an alternate frequency the increase rate was 41.31 cm^2 g^{-1}, or 15 % (Figure 6). Daily irrigation provided minimum and maximum values of 269.9 and 479.2 cm^2 g^{-1} under waters of 0.3 and 5.0 dS m^{-1}, respectively, and under an alternate irrigation frequency these respective values were 281.1 and 475.2 cm^2 g^{-1}.

The leaf area ratio (LAR) in papaya seedlings was only influenced by the electrical conductivity of the irrigation water and by the polymer in an independent manner (Table 4). It was verified that the increase in the water electrical conductivity by 1 dS m^{-1} increased the leaf area ratio by 28.38 cm^2 g^{-1}, or 17 %, changing from 168.3 to 196.68 cm^2 g^{-1} under the electrical conductivities of 0.3 and 5.0 dS m^{-1}, respectively (Figure 7). The increase in the polymer dose from 0.0 up to 0.6 g dm^{-3} reduced the leaf area ratio by 20%, with the respective means of 176.8 and 141.1 cm^2 g^{-1}, reaching the value of 171.9 cm^2 g^{-1} under the polymer dose of 1.2 g dm^{-3}.

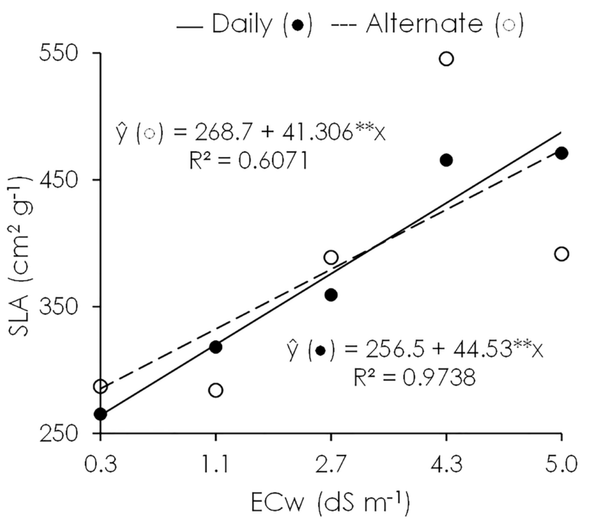

Figure 6. Specific leaf area (SLA) in Hawaii papaya seedlings at 55 days after sowing as a function of the electrical conductivity of the irrigation water (ECw), under daily (●) and alternate (○) irrigation frequencies. ° and **: significant at 10 and 1% of probability by the F-test, respectively.

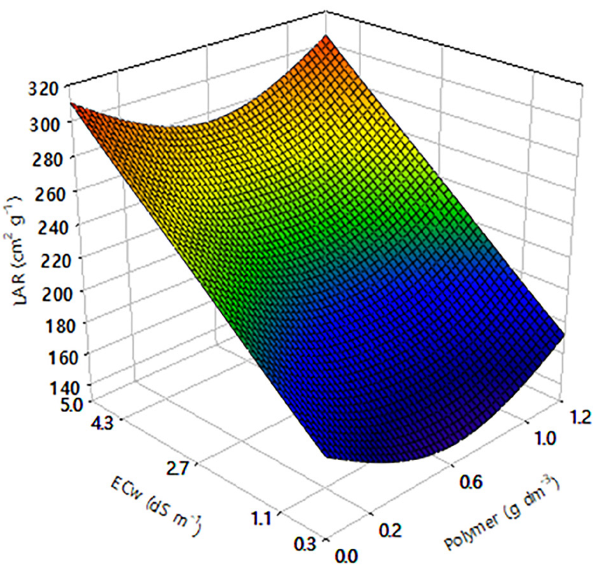

Figure 7. Leaf area ratio (LAR) in Hawaii papaya seedlings at 55 days after sowing, as a function of the polymer doses (P) in the substrate and the electrical conductivity of the irrigation water (ECw). ŷ = 168.3 – 114.8008P + 92.2550°P^2 + 28.3792**ECw, R^2 = 0.8628. ° and **: significant at 10 and 1% of probability by the F-test, respectively.

The leaf mass ratio (LMR) was only affected by the electrical conductivity of the irrigation water (Table 4), registering the lowest value of 0.55 and the highest value of 0.63 g g^{-1} under the respective water electrical conductivities of 0.3 and 3.5 dS m^{-1}, an increment of 15 % caused by the increase in the electrical conductivity of the irrigation water (Figure 8).

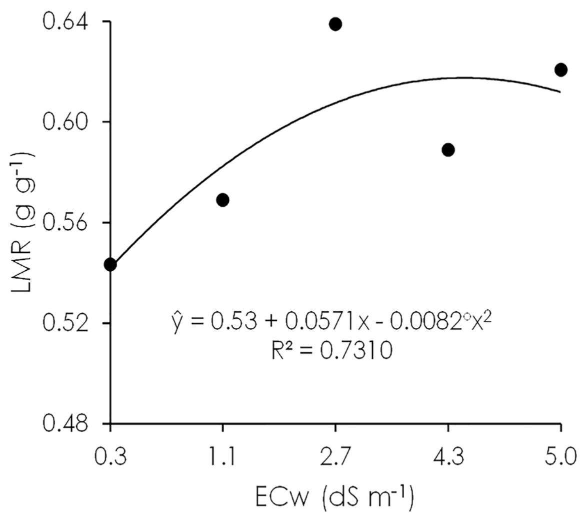

Figure 8. Leaf mass ratio (LMR) in Hawaii papaya seedlings at 55 days after sowing, as a function of the electrical conductivity of the irrigation water (ECw). °: significant at 10% of probability by the F-test.

For the Dickson quality index (DQI), in papaya seedlings, the effects of the polymer and the electrical conductivity of the irrigation water were observed in an isolated manner, with these results being influenced by the irrigation frequency (Table 4). The increase in the electrical conductivity of the irrigation water damaged the quality of the seedlings by the reduction in the Dickson index from 0.29 to 0.05 with daily irrigation (Figure 9A), and from 0.29 to 0.03 with irrigation in alternate days (Figure 9B), under the respective water electrical conductivities of 0.3 and 5.0 dS m^{-1}. The highest reduction rate as a function of the water electrical conductivity was obtained under alternate irrigation frequency, corresponding to 31 % at each increase of 1 dS m^{-1} in relation to the 24 % in daily in irrigation. Regarding the polymer, an increase in this index was observed up to the doses of 0.6 (Figure 9A) and 0.7 g dm^{-3} (Figure 9B), obtaining increases in relation to the zero dose from 0.29 to 0.34 (17 %) and from 0.29 to 0.33 (14 %), respectively. In relation to the container volumes, no gains were observed when this value was increased from 0.75 to 1.30 dm^3, under daily irrigation, with means of the Dickson index equivalent to 0.26 and 0.38, respectively (Figure 9C). However, under an alternate frequency, the volume increase from 0.75 to 1.30 dm^3 provided a gain of 0.19 in the Dickson index, with respective means of 0.16 and 0.35.

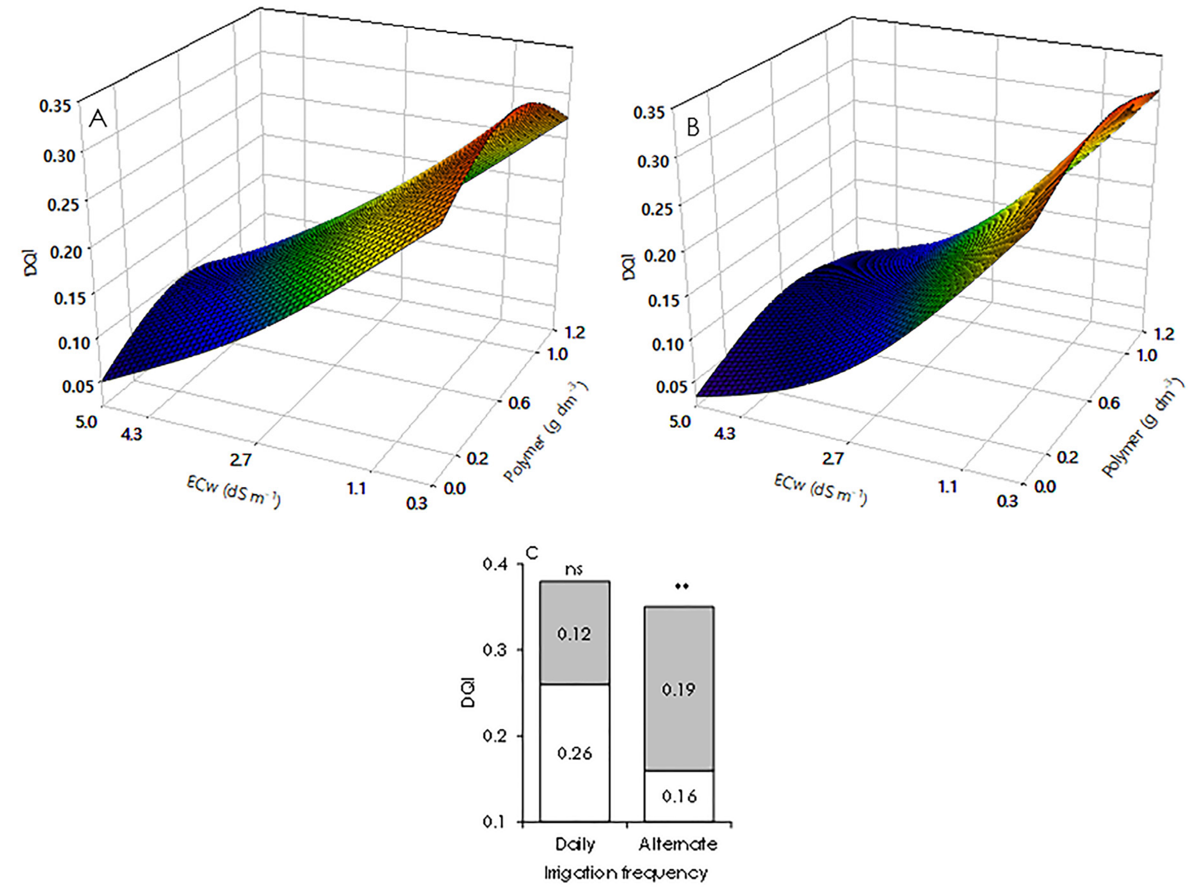

Figure 9. Dickson quality index (DQI) of Hawaii papaya seedlings at 55 days after sowing as a function of polymer doses (P) in the substrate and electrical conductivity of the irrigation water (ECw), under daily (A) and alternate (B) irrigation frequencies, and effects of the container volumes (C). $\hat{y}$ (A) = 0.31 + 0.1752P – 0.1568*P² – 0.0728**ECw + 0.0041°ECw², R^2 = 0.8339; $\hat{y}$ (B) = 0.32 + 0.1295P – 0.0922*P² – 0.1062**ECw + 0.0097*ECw², R^2 = 0.9802. ^{ns}, °, *and **: not significant and significant at 10, 5, and 1% of probability by the F-test, respectively; ■ Real effect: smallest container (0.75 dm^3) – largest container (1.30 dm^3).

Discussion

The reduction in the ratio between stem height and diameter in papaya seedlings under a higher irrigation frequency reflects greater sensitivity to water stress for the growth in height. In seedlings of yellow passion fruit (*Passiflora edulis* Sims.) (Carvalho et al., 2013) and sugar apple (*Annona squamosa* L.) (Silva et al., 2018a), the reduction in the irrigation frequency reduced the stem growth both in height and diameter. In pepper seedlings (*Capsicum baccatum*), no variation was observed in height when the seedlings were irrigated daily or in alternate days, although it increased when under two daily irrigations (Dassie et al., 2017). The increase in the electrical conductivity of the irrigation water also reduced the ratio between stem height and diameter since the elevation in the salt content reduces water availability and increases the absorption of toxic ions (Taiz et al., 2017). There is a growth reduction both in height and diameter in the seedlings due to salinity, as already observed for papaya (Sá et al., 2013a, b) and sugar apple (Silva et al., 2018a), with a more pronounced decrease in height; however, the intensity may be related with the age of the plant. In this sense, Santos et al. (2015), studying papaya, observed a growth reduction caused by the electrical conductivity of the irrigation water, observing the greatest impact in height compared to the diameter at 60 days after sowing, whereas at 90 and 120 days the effect of salinity was more intense on diameter. The polymer can increase water-use efficiency since it increased the relationship between height and diameter. Previously, this input has already allowed decreasing the irrigation frequency, from daily to alternate days, without leading, necessarily, to a growth increase in height and diameter, in yellow passion fruit seedlings (Carvalho et al., 2013).

The increase in the electrical conductivity of the irrigation water may change the allocation of biomass in seedlings, reflecting a possible adaptation of the plants to salt stresses. In papaya (Sá et al., 2013a) and sweet apple seedlings (Silva et al., 2018b) it was possible to verify reductions in the dry biomass of shoot and roots, although without compromising allocation, whereas in yellow passion fruit seedlings a greater sensitivity to salinity was observed regarding the accumulation of biomass in the root system to the detriment of the shoot part (Bezerra et al., 2014). However, Sá et al. (2013b), with papaya, Sá et al. (2015), with sweet apple, and Lima et al. (2020), with cashew (*Anacardium occidentale* L.), observed a greater reduction in the shoot biomass allocation of the seedlings with the increase in the electrical conductivity of the irrigation water. The effect of the increase in the conductivity of the irrigation water causes biomass decrease, although its intensity in the accumulation of shoot and root dry mater is associated with the ionic composition of the water (Cavalcante et al., 2010). The application of a water-absorbing polymer to the substrate can favor the allocation of biomass in the shoot part, as observed by Carvalho et al. (2013), considering that a lower root growth need may occur due to the better hydric condition. The age of the seedlings and the irrigation management may change the effect of the water-absorbing polymer (Marques et al., 2013; Silva et al., 2018b).

Root density can indirectly express the growth and development of roots to occupy the edaphic environment, and its increment can provide a wider use of water nutrients by plants. The reduction in the root mass values with the increase in the electrical conductivity of the irrigation water, as observed in seedlings of papaya (Sá et al., 2013a, b), yellow passion fruit (Bezerra et al., 2014), and sweet apple (Silva et al., 2018b), results in lower root density, and this effect can be mitigated with a higher irrigation frequency (Figure 3). The increase in the irrigation frequency tends to favor the accumulation of mass in the roots of seedlings (Carvalho et al., 2013; Silva et al., 2018b), even under saline conditions, considering that it favors the dilution and/or leaching of salts. The incorporation of the polymer in the substrate can also stimulate the improvement in water-use efficiency, allowing a reduced irrigation frequency without compromising the accumulation of mass in the roots (Carvalho et al., 2013). However, it is highlighted that, under special conditions, the application of the water-absorbing polymer may cause root development disorders since the moisture excess in the substrate can favor anaerobic conditions in the rhizosphere, limiting its respiration, growth, and the photosynthetic process (Navroski et al., 2015).

Water deficit may result in loss of the leaf area either due to a lower leaf production or to a reduction in the leaf blade area, which can change the mass allocation among plant organs, as well as plant growth, due to the reduction in the photosynthetic area. In this work, a correlation ($\rho = -0.33$; $p = 0.0028$) of the leaf blade area was observed with the relationship between shoot and root dry matter, that is, larger leaves may result in greater mass allocation in the roots. Managements that favor better water use can result in a larger leaf area (Carvalho et al., 2013). Fagundes et al. (2015) observed a larger leaf area and number of leaves in yellow passion fruit seedlings with the increase in the polymer content in the substrate, although with higher intensity for the leaf area. The increase in salinity can also change the area and the photosynthetic apparatus (Taiz et al., 2017). In seedlings of papaya (Sá et al., 2013b) and yellow passion fruit (Bezerra et al., 2019), reductions were verified in the number of leaves and in the leaf area with the increase in water electrical conductivity, with more intense effects for the leaf area. Therefore, it is necessary to adequate the irrigation management in order to mitigate the effects of salt excess in the irrigation water since allometric or morphometric allocations are commonly-employed mechanisms by plants when exposed to water or salt stress conditions. Containers with larger volumes can also favor the increase in the number of leaves and, consequently, in the leaf area, considering that they offer better conditions for seedlings development (Costa et al., 2010).

The ratio between leaf area and root dry matter (LA/RDM) represents the balance between the organs of photosynthetic production and those responsible for water and nutrient absorption, two processes of utter importance to vegetal life. In the present study, the harmful effect of the increase in the water electrical conductivity was more expressive in root and total dry matter than in the leaf area, as observed in the relationship between leaf area and root dry matter and in the leaf area ratio, respectively. The leaf area ratio is an expressive parameter for the capture potential of photosynthetically active radiation, in which lower values imply greater photosynthetic efficiency (Fagundes et al., 2015). Leaf alterations were also observed, such as reductions in size and thickness, with the increase in the specific leaf area being the indirect result of the production of thinner leaves (Bezerra et al., 2019), resulting in the reduction of efficiency in the use of solar irradiance (Taiz et al., 2017), considering that higher values indicate lower concentrations of chloroplasts and enzymes related to photosynthesis (Evans & Pooter, 2001), even with greater mass allocation to the leaves in comparison with the remaining organs of the seedlings, such as observed in the leaf mass ratio.

In view of the exposed and in the conditions of this study, it is verified that the leaves were the less damaged organs with the exposure of the plant to soil salinity through irrigation. In most cases, one of the first effects expressed by the plants, when subjected to high salt concentrations, is a rapid and intense growth reduction (Sá et al., 2013b), which in the present study was more intense in the roots. The increase in the electrical conductivity also increased the specific leaf area and the leaf area ratio in yellow passion fruit seedlings (Bezerra et al., 2019), besides increasing this last index also in papaya seedlings (Santos et al., 2015). However, Sá et al. (2013b), when evaluating papaya seedlings, observed a reduction in the leaf area ratio with the increase of the electrical conductivity of the irrigation water, although considering only the shoot dry mass in the calculation of this index, which may justify possible distinctions. As for the leaf mass ratio in sweet apple seedlings, Silva et al. (2018b) observed no effects of the electrical conductivity of the irrigation water.

The use of a water-absorbing polymer probably favored the storage of water since these polymers increase the diameter of water-storing pores (Carvalho et al., 2013), and also decrease nutrient leaching, besides contributing to soil conditioning by optimizing its physical-chemical properties (Fagundes et al., 2015). Fagundes et al. (2014), when studying substrate formulations for the production of citrus rootstocks, observed similar behavior in *Citrus limonia* and *Poncirus trifoliata*, verifying a relative increment in root dry matter in comparison with the leaf area with the addition of polymer to the substrate. In passion fruit seedlings, the use of polymer reduced the leaf area ratio (Carvalho et al., 2013; Fagundes et al., 2015).

Alterations in the allometric and morphophysiological indices result in changes in the seedling pattern, with the Dickson Quality Index (DQI) constituting a global parameter that better reflects the seedling quality. As observed in this work, the increase in electrical conductivity resulted in the reduction of quality (DQI) in the papaya seedlings, results also corroborated in seedlings of sweet apple (Silva et al., 2018a) and yellow passion fruit (Medeiros et al., 2016; Bezerra et al., 2019). It is then highlighted that the irrigation frequency modifies the effects of salinities, which are intensified under a lower frequency, probably due to the effect of lower salt dilution. Regarding the water-absorbing polymer, the beneficial effect in the production of papaya seedlings is limited to its concentration in the substrate, as also observed in seedlings of *Eucalyptus dunnii* (Navroski et al., 2016). This behavior can be attributed to the reduction of water losses and, consequently, to the mitigation of water stress provided by the water-retaining polymer, thus causing greater production and accumulation of total mass by the seedlings. Larger containers can also provide papaya seedlings with better quality (Costa et al., 2010), with the irrigation frequency being a decisive factor for the effect of container volumes on the quality of papaya seedlings.

Conclusions

The higher irrigation frequency and the use of water-absorbing polymer in the substrate indirectly mitigate the negative effects of salinity on the production of seedlings of the papaya cv. 'Sunrise Solo'.

Saline waters with electrical conductivity up to 2.6 and 1.9 dS m^{-1} can be employed in the production of seedlings of the papaya cv. 'Sunrise Solo' when irrigated daily and in alternate days, respectively.

The use of 0.6 g dm^{-3} of water-absorbing polymer in the substrate is recommended for the production of quality seedlings of the papaya cv. 'Sunrise Solo'.

For the production of seedlings of the papaya cv. 'Sunrise Solo', the plants can be produced in containers with capacity of 0.75 or 1.30 dm^{-3}, under daily irrigation.

Acknowledgments

This experiment was performed with the support of the Coordination for the Improvement of Higher Education Personnel (CAPES), of the Brazilian National Council for Scientific and Technological Development (CNPq), and of the Hydroplan®-EB Company.

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.