

Water restriction and sewage sludge-based substrates affect the growth of *Enterolobium contortisiliquum* seedlings

Restrição hídrica e substratos à base de lodo de esgoto afetam o crescimento de mudas de *Enterolobium contortisiliquum*

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ABSTRACT

Using sewage sludge in agriculture can be an alternative for the sustainable production of tree species. When combined with automatic irrigation, it can improve system efficiency and seedling quality. This study evaluated the growth, water use, and water productivity of *Enterolobium contortisiliquum* (pacara earpod tree) seedlings grown in different biosolid-based substrates and irrigation levels. The experiment followed a randomized block design in a split-plot arrangement, with four substrate treatments (0%, 50%, 75%, and 100% biosolids) and four irrigation levels (57%, 67%, 83%, and 100% of crop water requirement). An automatic irrigation controller with a soil moisture sensor was installed for the 100% irrigation treatment in each substrate. The variables analyzed were seedling height, stem diameter, shoot dry mass, and water productivity. Seedlings grown in 100% biosolid substrate showed greater height and diameter when irrigated at higher levels with sewage sludge. However, irrigation levels had no significant effect on seedlings grown in substrates with 0%, 50%, or 75% biosolids. Shoot dry mass was not affected by irrigation level. The highest shoot dry mass and water productivity occurred in seedlings grown in 75% biosolid substrate with 83% of water replacement.

Index terms: Automatic irrigation system; tree species; circular economy; Sustainable Development Goals (SDGs).

RESUMO

A utilização de lodo de esgoto na agricultura pode ser uma alternativa para a produção sustentável de espécies arbóreas. Quando combinada com irrigação automatizada, pode melhorar a eficiência do sistema e a qualidade das mudas. Este estudo avaliou o crescimento de mudas de *Enterolobium contortisiliquum* (tamboril) cultivadas em diferentes substratos à base de biossólido e níveis de irrigação. O experimento foi conduzido em delineamento em blocos casualizados em arranjo de parcelas subdivididas, com quatro tratamentos de substrato (0%, 50%, 75% e 100% de biossólido) e quatro níveis de irrigação (57%, 67%, 83% e 100% da necessidade hídrica da planta). Um controlador automático de irrigação com sensor de umidade do solo foi instalado para o tratamento com 100% de reposição hídrica em cada tipo de substrato. As variáveis analisadas foram altura, diâmetro do caule, massa seca da parte aérea e produtividade hídrica. Mudas cultivadas em substrato com 100% de biossólido apresentaram maior altura e diâmetro quando irrigadas com maiores volumes de água. No entanto, os níveis de irrigação não afetaram as mudas cultivadas nos substratos com 0%, 50% e 75% de biossólido. A massa seca da parte aérea não foi afetada pelos níveis de irrigação. Os maiores valores de massa seca da parte aérea e produtividade hídrica foram observados em mudas cultivadas em substrato com 75% de biossólido e 83% de reposição hídrica.

Termos para indexação: Sistema automático de irrigação; espécies arbóreas; economia circular; Objetivos do Desenvolvimento Sustentável (ODS).

Introduction

Anthropogenic activities have caused environmental degradation and disrupted ecosystems around the world. To address these impacts, efforts now focus on sustainable alternatives, including the environmentally-sound management of municipal solid waste. (Singh & Agrawal, 2008; Sugurbekova et al., 2023). One example is sewage sludge, a by-product of wastewater treatment. Managing this waste remains a major challenge and requires strategies aligned with sustainable development goals and circular economy principles to minimize environmental impacts and recover valuable resources (Kacprzak et al., 2017; Nascimento et al., 2022).

Sewage sludge is a biologically active mixture of water, organic matter, living and dead microorganisms, as well as toxic organic and inorganic contaminants (Campo et al., 2021). When properly treated and stabilized, it becomes biosolids safe for use in agriculture. Treatment reduces or eliminates pathogens and

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toxic substances, allowing their use in substrate formulations (Abreu et al., 2017b; Sugurbekova et al., 2023). Biosolids have proven effective in forest seedling production by supplying organic matter and essential nutrients for plant growth (Abreu et al., 2017a; Abreu et al., 2019). They also improve soil physical and chemical properties in degraded areas (Sampaio et al., 2012).

The quality of forest seedlings plays a key role in reforestation and the restoration of degraded areas, strategies that help mitigate climate change by sequestering carbon from the atmosphere and regulating temperature and the hydrological cycle (Bastin et al., 2019; Kumar et al., 2015; Ota et al., 2020). In Brazil, forest restoration in the Atlantic Forest, one of the world's main biodiversity hotspots, is mainly carried out by planting native tree seedlings (Oliveira & Engel, 2017). *Enterolobium contortisiliquum* (Vell.) Morong, known as tamboril or pacara earpod tree, is a fast-growing species of the Fabaceae family native to the biome and typical of tropical seasonal dry forests (Cardoso et al., 2021). It is considered an excellent option for reforestation (Lorenzi, 2002).

The production of forest seedlings depends on factors such as water supply, nutrient availability, and substrate composition. These factors must support full physiological development and healthy root systems to enhance high survival rates and good field performance after transplanting (Gregorio et al., 2017; Grossnickle & MacDonald, 2018; Manca et al., 2020; Shalizi et al., 2019). Water restriction is a critical factor during the early growth of seedlings. With decreasing water availability and growing scarcity in many regions, it is necessary to evaluate how different water conditions affect the growth of *E. contortisiliquum* seedlings. Efficient water use in forest nurseries is also critical, as poor irrigation management can lead to significant waste, up to 70% of the water applied (Dumroese et al., 2005; Li et al., 2022). Water use efficiency, also known as water productivity, is a widely used metric in agriculture and has also been applied to tree seedling production (Silva et al., 2022).

Given this context, integrating sewage sludge as a substrate component and nutrient source for the production of *E. contortisiliquum* seedlings, alongside automated irrigation management, offers a promising and sustainable strategy. This approach supports proper urban waste disposal, reduces input costs for seedling production, and improves water use efficiency. These actions align with the Sustainable Development Goals (SDGs), a key pillar of the UN 2030 Agenda (Aly, Elsayah, & Ryan, 2022), especially goals 6 (clean water and sanitation), 13 (climate action), and 15 (life on land). This study aimed to evaluate the growth of pacara earpod tree (*E. contortisiliquum*) seedlings in biosolid-based substrates under different irrigation depths. This topic is novel in seedling production research due to the lack of studies addressing the interaction between irrigation volumes and biosolid-based substrates.

Material and Methods

The experiment was conducted from May to October 2024 at the Federal Rural University of Rio de Janeiro, Seropédica campus (22°45'48"S; 43°41'19"W), Rio de Janeiro, Brazil. According to the Köppen classification, the region has an Aw climate, with average annual precipitation between 1,300 and 1,600 mm and temperatures ranging from 22 to 24 °C (Alvares et al., 2013) with well recognized simple rules and climate symbol letters. In Brazil, climatology has been studied for more than 140 years, and among the many proposed methods Köppen's system remains as the most utilized. Considering Köppen's climate classification importance for Brazil (geography, biology, ecology, meteorology, hydrology, agronomy, forestry and environmental sciences).

Enterolobium contortisiliquum was directly sown, with two seeds per polypropylene tube (280 cm³), using substrates composed of biosolid (BS) and the commercial product Max Fertil® (MF). Four substrate treatments were tested: 100% BS (S₁₀₀), 75% BS + 25% MF (S₇₅), 50% BS + 50% MF (S₅₀), and 0% BS (S₀). The biosolid was produced by sewage treatment plants operated by the Rio de Janeiro State Water and Sewage Company (CEDAE), using residential and commercial waste and excluding industrial effluents. Silva et al. (2022) performed the chemical characterization of the biosolid according to official procedures established by CONAMA Resolution 498 (Brasil, 2020). Selected chemical and physical parameters are presented in Table 1. The physical properties are similar to those of humic soils. According to the manufacturer, Max Fertil® has a bulk density of 0.31 g m⁻³ and a water retention capacity of 90%.

According to the water retention curves (Equations 1, 2, 3 and 4), the water content at -10 kPa for substrates S₀, S₅₀, S₇₅, and S₁₀₀ was 0.323, 0.335, 0.351, and 0.323 cm³ cm⁻³, respectively.

$$\theta_0 = 0.0241 + \frac{0.7648}{\left[1 + (25.22 \cdot h)^{1.17}\right]^{0.1453}} \quad (1)$$

$$\theta_{50} = 0.0223 + \frac{0.7800}{\left[1 + (21.70 \cdot h)^{1.17}\right]^{0.1453}} \quad (2)$$

$$\theta_{75} = 0.0201 + \frac{0.8074}{\left[1 + (18.85 \cdot h)^{1.17}\right]^{0.1453}} \quad (3)$$

$$\theta_{100} = 0.1045 + \frac{0.7885}{\left[1 + (85.88 \cdot h)^{1.19}\right]^{0.1597}} \quad (4)$$

where θ is the substrate moisture (cm³ cm⁻³) and h is the matric potential (kPa).

After sowing, the tubes were placed in plastic trays, each holding up to 54 tubes. Thinning was performed after seedling emergence, leaving the most vigorous plant in each tube. At 21 days after sowing, the seedlings were rearranged in alternating positions, with 24 plants per tray (Figure 1A).

The experiment followed a randomized block design in a split-plot arrangement with four types of substrate as main plots and four irrigation volumes as subplots. Each subplot contained six plants, with four replications, totaling 384 experimental units.

Throughout the experiment, seedlings were irrigated using local water via drip microirrigation with PCJ-HCNL emitters (Netafim), which delivered flow rates of 3.0, 2.5, 2.0, and 1.7 L h⁻¹. Irrigation was managed using the automatic actuator for irrigation (AAI), proposed by Medici et al. (2010) (Figure 1B, C). For each substrate, emitters were installed in the treatment with the highest flow rate (V₄), ensuring full replacement of the plant's water demand. The other flow rates corresponded to 83% (V₃), 67% (V₂), and 57% (V₁) of this reference value.

Meteorological monitoring was performed using data from the National Institute of Meteorology (INMET) Automatic Weather Station in Seropédica. In addition, digital thermo-hygrometers

(model HT-4010, Icel) were installed, recording data every 30 minutes. Based on meteorological data, daily reference evapotranspiration (ET_o) was estimated using the Penman-Monteith method (FAO-56) (Allen, Pereira, & Smith, 1998).

Seedling height (H) and stem diameter (D) were measured every 21 days using a graduated ruler and caliper, respectively. When seedlings reached the commercial standard for height and diameter, the four individuals closest to the mean in each replicate were selected for the determination of total dry mass (TDM) on a scale with 0.001 g precision. The selected seedlings were cut, separated into shoots and roots, placed in paper bags, and dried in an oven at 65 °C until constant weight. Water productivity was calculated as the ratio of total dry mass to the volume of water applied.

The data were tested for normality and homogeneity of variances using the Shapiro-Wilk (Shapiro & Wilk, 1965) and Bartlett (Bartlett, 1937) tests, respectively, in the R software version 4.4.3 (R Core Team, 2025), to verify the assumptions of the analysis of variance (ANOVA). Treatment effects were evaluated by ANOVA for all measured parameters. When significant differences were detected (p ≤ 0.05), regression analysis was performed to model the responses.

Table 1: Chemical and physical characteristics of biosolid.

Chemical characteristics*						
N	P	K	S	Ca	Mg	OC
----- % -----						
1.5	0.61	0.16	0.89	1.57	0.32	9.41
Zn	Fe	Mn	Cu	B		
----- mg kg ⁻¹ -----						
722.7	20773.3	184.5	164.3	12.1		
Physical characteristics**						
TP***			PD		BD	
----- cm cm ⁻³ -----			----- g cm ⁻³ -----			
0.57			1.71		0.74	

*Silva et al. (2022); **Carvalho et al. (2021) and Bueno et al. (2021); ***TP – total porosity; PD – particle density; BD – bulk density.

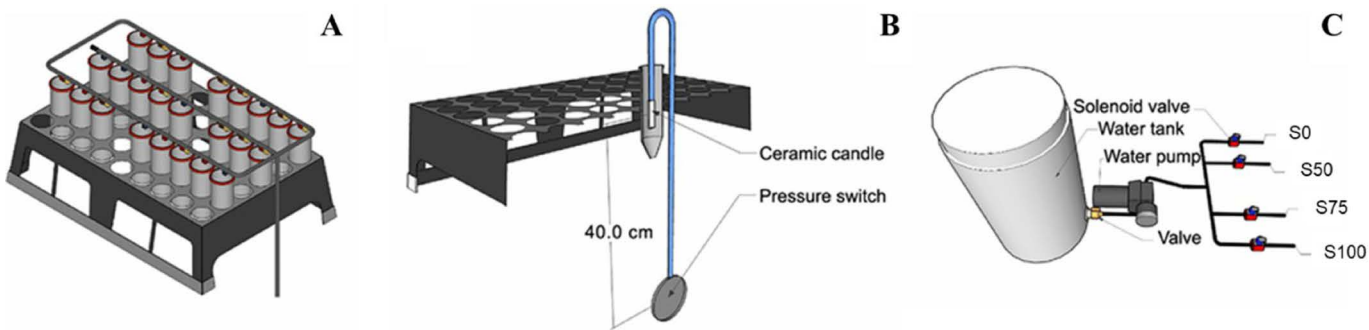


Figure 1: Arrangement of the tubes in the tray (A), positioning of the AAI in the tube (B), and pumping system coupled to the solenoid valves (C). Source: Silva et al. (2024).

Results and Discussion

Meteorological aspects and volume of water applied

Accumulated reference evapotranspiration (ETo Ac) during the experiment was 448.1 mm (Figure 2). The highest values occurred between September 9-29 (101.3) and September 30 – October 21 (84.4 mm). Most of the experiment took place during winter, the driest season in the region. Of the 127 experimental days, rainfall was recorded on only 30 days, totaling 109.8 mm of accumulated precipitation (PPT Ac). The highest precipitation was 27.4 mm (June 17-30) and 29.6 mm (July 29-August 11). Throughout the study period, accumulated

ETo exceeded accumulated precipitation. Rainfall exceeded ETo on only 14 days.

Temperature variation during the evaluation period was small, with an average temperature amplitude of 12 °C. The highest temperature (39.6 °C) was recorded between September 30 and October 21, while the lowest (9.3 °C) occurred between August 12 and 25. Maximum relative humidity remained stable, ranging from 94% to 96%. The lowest relative humidity was 13%, recorded between September 9 and 29.

During the experiment, the number of activations (Nac) of the irrigation system and the volume of water applied varied according to substrate composition and meteorological conditions (Figure 3).

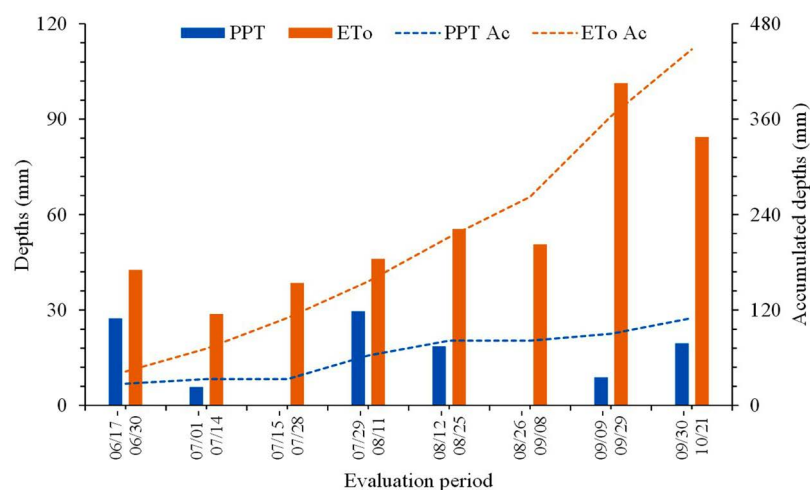


Figure 2: Biweekly precipitation (PPT) and reference evaporation (ETo) recorded during the experimental period.

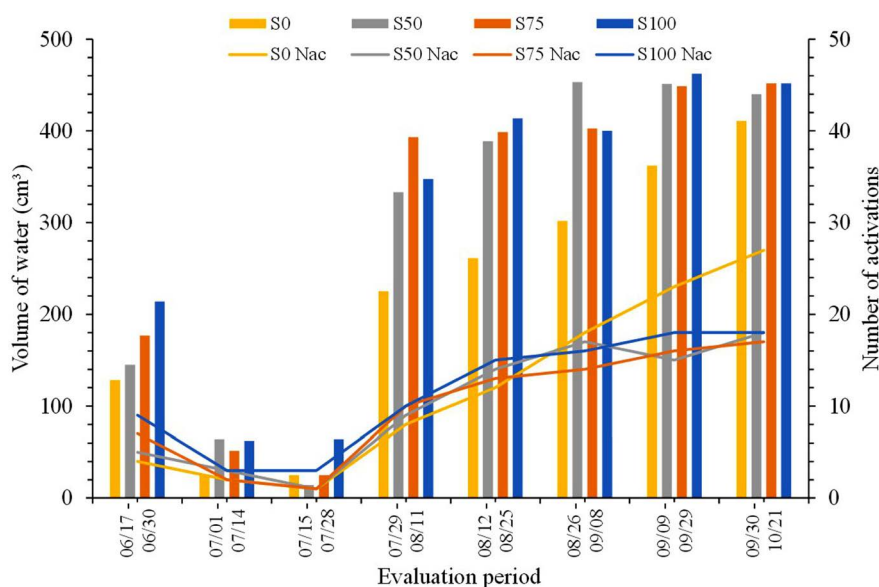


Figure 3: Biweekly number of activations (Nac) of the irrigation system and total volume of water received (irrigation + precipitation) by seedlings grown in substrates S_0 , S_{50} , S_{75} , and S_{100} under 100% replacement of water demand (V_4).

From 42 days after sowing (July 29 onwards), water demand of pacara earpod tree seedlings increased considerably, resulting in more frequent irrigation system activations. This increase coincided with higher evapotranspiration and reduced precipitation during the same period, both of which directly contributed to greater water demand. The water requirement of plants is closely linked to local climate and their developmental stage. During the early growth phase (June 17 to July 28), water demand was significantly lower, possibly due to the species' greater resilience to water regime variations in this period, as noted by Araujo et al. (2021).

The period of highest evapotranspiration (September 9 to 29) coincided with the lowest relative humidity (13%) recorded, reduced precipitation, and increased frequency of activation of the irrigation system in most substrates (Figure 3). In low-humidity environments, the difference between plant and atmospheric water potentials is accentuated, intensifying water loss through transpiration (Taiz et al., 2017). This condition increases plant water demand, which explains the higher volume of water required during this period.

Under 100% replacement of plant water demand (V_4), the irrigation system was activated 95, 82, 80, and 92 times for substrates S_0 , S_{50} , S_{75} , and S_{100} , respectively. The total volume of water applied to each substrate under the different flow rates is shown in Table 2.

Table 2: Total volume of water (irrigation + precipitation, L per plant) applied to *E. contortisiliquum* seedlings grown in different substrate compositions.

Substrate	Volume of water (L plant ⁻¹)			
	V_1	V_2	V_3	V_4
S_0	1.05	1.21	1.47	1.74
S_{50}	1.36	1.57	1.93	2.29
S_{75}	1.39	1.61	1.98	2.35
S_{100}	1.43	1.66	2.04	2.42

V_1 = 57% replacement of water demand, V_2 = 67%, V_3 = 83%, and V_4 = 100%.

In general, data from the automatic irrigation system show that seedlings grown in biosolid-based substrates (S_{50} , S_{75} , and S_{100}) required a higher volume of water compared to those grown in the commercial substrate Max Fertil[®], despite their higher water retention, especially in S_{50} and S_{75} . Biosolid-based substrates have higher microporosity, which increases water retention compared to commercial substrates. This characteristic explains the lower irrigation frequency and the higher volume of water applied by irrigation (Abreu et al., 2017b). Substrates with higher water retention capacity typically require fewer irrigation events but demand a larger volume per cycle to restore optimal moisture levels (Neves et al., 2021).

Seedling growth and quality

In substrate S_{100} , increasing irrigation volumes significantly enhanced plant height and stem diameter (Figure 4D). Under full irrigation (V_4), seedlings reached an average height of 22.95 cm and stem diameter of 4.53 mm, both higher than under partially replacements (V_1 , V_2 , and V_3). For the other substrates (S_0 , S_{50} , and S_{75}), variations in irrigation volumes based on water replacement percentages did not affect seedling height or stem diameter (Figure 4A-C). These results highlight that plant growth in biosolid-only substrate (S_{100}) is highly responsive to irrigation volume. The limited growth observed under lower irrigation levels suggests that water deficit may have restricted seedling development, despite the substrate's high water retention capacity.

Low water availability compromises protein synthesis and slows mitotic activity, reducing cell division and expansion, processes essential for plant development (Taiz et al., 2017). Ferreira et al. (2023) reported a linear decrease in height and stem diameter of *E. contortisiliquum* seedlings with increasing water restriction, suggesting that reduced growth is a physiological strategy the species uses to cope with abiotic stress, although it may limit seedling quality. Intermediate irrigation volumes may have maintained seedling development within a functional range, though insufficient to support maximum growth performance.

In contrast, the growth of *E. contortisiliquum* seedlings was not affected by reduced irrigation volumes in substrates S_0 , S_{50} , and S_{75} . This suggests that the composition of these substrates provided stable conditions for the plants' physiological responses, even under moderate water deficit. Such a characteristic is particularly advantageous in the context of climate change and increasing water scarcity, where sustainable and efficient seedling production strategies are essential (Li et al., 2022).

Water productivity was influenced by irrigation volumes in all biosolid-based substrates (Figure 5). Seedlings grown under the lowest irrigation level (V_1) in substrates S_{50} , S_{75} , and S_{100} showed higher water use efficiency compared to those irrigated with higher volumes in the same substrates (Figure 5 B-D).

Water productivity, expressed as the ratio between biomass produced and the volume of water applied, reflects plant water use efficiency (WUE), and serves as an important indicator of sustainability in seedling production systems. In this study, lower irrigation volumes in substrates S_{50} , S_{75} , and S_{100} resulted in higher WP values compared to higher volumes (Table 3), indicating more efficient water use under reduced supply. Araujo et al. (2021) observed that WUE in pacara earpod tree seedlings was unaffected by different water regimes, highlighting the species' resilience and efficiency during early development. Similarly, Peroni et al. (2021) observed that seedlings showed more balanced biomass allocation when subjected to a reduced irrigation depth.

Irrigation volume had no significant effect on the shoot dry mass of *E. contortisiliquum* seedlings in any substrate. Mean shoot dry mass values were 1.77 (S_0), 1.95 (S_{50}), 2.34 (S_{75}), and 2.25 (S_{100}) (Table 3).

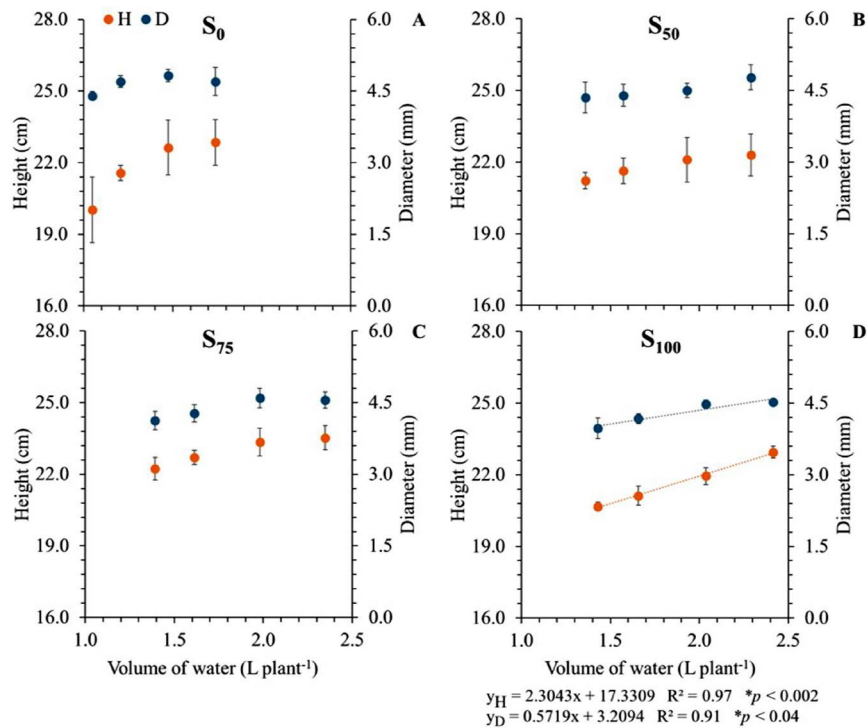


Figure 4. Height (orange) and stem diameter (blue) of *E. contortisiliquum* seedlings grown in substrates S₀ (A), S₅₀ (B), S₇₅ (C), and S₁₀₀ (D) as a function of the total water volume applied per plant.

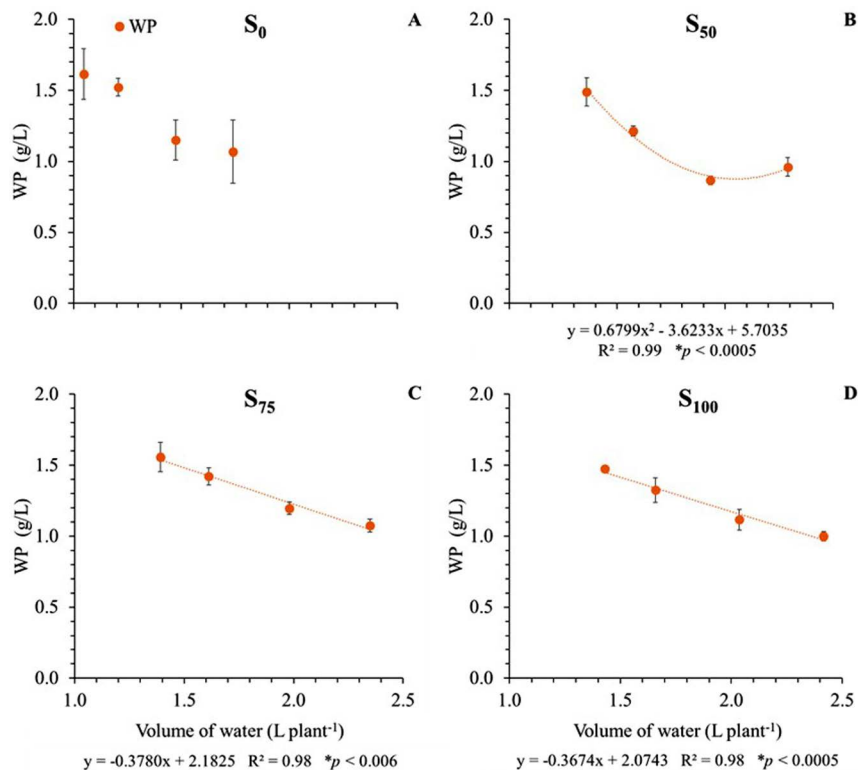


Figure 5: Water productivity (WP) of *E. contortisiliquum* seedlings in substrates S₀ (A), S₅₀ (B), S₇₅ (C), and S₁₀₀ (D) as a function of the total volume of water applied per plant.

Table 3: Comparison of substrates at the same water replacement level for seedling height, stem diameter, shoot dry mass, and water productivity of *E. contortisiliquum* grown in different substrate compositions.

Substrate	S ₀	S ₅₀	S ₇₅	S ₁₀₀
Height (cm)				
V ₁	20.03 ^{ns}	21.23 ^{ns}	22.23 ^{ns}	20.68 ^{ns}
V ₂	21.58 ^{ns}	21.63 ^{ns}	22.70 ^{ns}	21.13 ^{ns}
V ₃	22.63 ^{ns}	22.10 ^{ns}	23.35 ^{ns}	21.95 ^{ns}
V ₄	22.85 ^{ns}	22.30 ^{ns}	23.53 ^{ns}	22.95 ^{ns}
Diameter (mm)				
V ₁	4.4 ^{ns}	4.4 ^{ns}	4.1 ^{ns}	4.0 ^{ns}
V ₂	4.7 ^{ns}	4.4 ^{ns}	4.3 ^{ns}	4.2 ^{ns}
V ₃	4.8 ^{ns}	4.5 ^{ns}	4.6 ^{ns}	4.5 ^{ns}
V ₄	4.7 ^{ns}	4.8 ^{ns}	4.6 ^{ns}	4.5 ^{ns}
Shoot dry mass (g)				
V ₁	1.68 ^{ns}	2.03 ^{ns}	2.17 ^{ns}	2.11 ^{ns}
V ₂	1.84 B	1.91 AB	2.29 A	2.20 AB
V ₃	1.70 B	1.67 AB	2.37 A	2.28 AB
V ₄	1.86 ^{ns}	2.20 ^{ns}	2.52 ^{ns}	2.42 ^{ns}
Water productivity (g L ⁻¹)				
V ₁	1.61 ^{ns}	1.49 ^{ns}	1.56 ^{ns}	1.48 ^{ns}
V ₂	1.52 A	1.22 B	1.42 AB	1.33 AB
V ₃	1.15 AB	0.87 B	1.20 A	1.12 AB
V ₄	1.07 ^{ns}	0.96 ^{ns}	1.07 ^{ns}	1.00 ^{ns}

V₁ = 57% replacement of water needs, V₂ = 67%, V₃ = 83%, and V₄ = 100%. Values are means. Means followed by the same letter in a row do not differ significantly according to the Kruskal-Wallis' test followed by Dunn's post hoc test at 5% probability level. ^{ns}Not significant.

When comparing substrates under the same irrigation level, significant differences in shoot dry mass were observed at 67% (V₂) and 83% (V₃) water replacement. The highest mean values (2.29 and 2.37 g, respectively) were recorded in the substrate S₇₅ (Table 3). For water productivity, the highest values were found in S₀V₂ (1.52 g L⁻¹) and S₇₅V₃ (1.20 g L⁻¹). Substrate composition had no significant effect on seedling height or stem diameter.

The higher values of shoot dry mass observed in substrate S₇₅ under intermediate irrigation levels (V₂ and V₃) may be associated with the chemical and physical benefits of biosolids. This result aligns with Cabreira et al. (2017), who found a progressive increase in biomass with biosolid addition in *Peltophorobium dubium*, *Lafoensia pacari*, and *Ceiba speciosa*. According to the authors, this response can be attributed to improved nutrient availability and soil structure provided by biosolid-enriched substrates. Similarly, Abreu et al. (2017b) found that a higher proportion of biosolids in the substrate increased nitrogen (N), phosphorus (P), and potassium (K) levels, which directly contribute to biomass accumulation in seedlings.

When comparing substrates under the same irrigation level, water productivity showed a significant difference only at V₂ and V₃, with the highest values observed in S₀ and S₇₅, respectively. These results suggest that substrate S₇₅ required slightly more water than the commercial substrate (S₀) to achieve maximum water use efficiency, possibly due to its higher water retention capacity (Abreu et al., 2017b; Neves et al., 2021). Substrate moisture content and composition directly influence water retention and availability within containers (Schulker et al., 2020). Thus, irrigation management should be tailored considering the physical and chemical properties of each substrate to optimize water productivity and support seedling growth and development without waste.

Conclusions

Higher irrigation depths improved the growth of *E. contortisiliquum* seedlings cultivated in a 100% biosolid-based substrate. The substrate composed of 75% biosolid and 25% Max Fertil® led to consistent growth performance when 83% of the

seedlings' water demand was supplied through AAI, particularly in terms of biomass accumulation and water productivity. These findings support the use of biosolid-based substrates combined with automated irrigation as a sustainable strategy for the commercial production of *E. contortisiliquum* seedlings for ecological restoration.

Author contribution

Conceptual idea: Moraes, I. M.; Arthur Júnior, J. C.; Carvalho, D. F.; Methodology design: Moraes, I. M.; Arthur Júnior, J. C.; Carvalho, D. F.; Data collection: Moraes, I. M.; Carvalho, D. F.; Data analysis and interpretation: Moraes, I. M.; Pessoa, V. J. C. S.; Carvalho, D. F.; and Writing and editing: Pessoa, V. J. C. S.; Suzano, E. M. G.; Arthur Júnior, J. C.; Carvalho, D. F.

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Data availability statement

Data available upon request to authors.

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