Agrociencia

SUCTION IRRIGATION IN ORNAMENTAL PLANTS: ANALYSIS OF WATER CONSUMPTION IN *Dimorphotheca ecklonis* DC. AND *Graptopetalum paraguayense* (N.E.Br.) E. Walther

María Magdalena **Nevárez-Favela**[1], Abel **Quevedo-Nolasco**[1*], J. Cruz **García-Albarado**[2],
Martin Alejandro **Bolaños-González**[1], Adolfo **López-Pérez**[1],
Moisés **Márquez-Velázquez**[3], Ruben **Esparza-Orozco**[1]

[1]Colegio de Postgraduados Campus Montecillo. Postgrado en Hidrociencias. Carretera México-Texcoco km 36.5 Montecillo, Texcoco, State of Mexico, Mexico. C. P. 56264.
[2]Colegio de Postgraduados Campus Córdoba. Postgrado en Paisaje y Turismo Rural. Carretera Córdoba-Veracruz km 348, Manuel León, Amatlán de los Reyes, Veracruz, Mexico. C. P. 94953.
[3]Colegio de Postgraduados Campus Montecillo. Postgrado Edafología. Carretera México-Texcoco km 36.5 Montecillo, Texcoco, State of Mexico, Mexico. C. P. 56264.
* Author for correspondence: abcdqn@gmail.com

Citation: Nevárez-Favela MM, Quevedo-Nolasco A, García-Albarado JC, Bolaños-González MA, López-Pérez A, Márquez-Velázquez M, Esparza-Orozco R. 2025. Suction irrigation in ornamental plants: Analysis of water consumption in *Dimorphotheca ecklonis* DC. and *Graptopetalum paraguayense* (N.E.Br.) E. Walther. **Agrociencia.** https://doi.org/ 10.47163/agrociencia.v59i6.3381

Editor in Chief:
Dr. Fernando C. Gómez Merino

Received: February 16, 2025.
Approved: September 19, 2025.
Published in Agrociencia:
September 25, 2025.

ABSTRACT

Suction irrigation in ornamental species provides only the amount of water required by the soil-plant-atmosphere system, reducing water losses due to evaporation, runoff, and percolation. In this work, an experiment was conducted in subdivided plots arranged in randomized blocks to evaluate the daily and cumulative water consumption of *Dimorphotheca ecklonis* DC. and *Graptopetalum paraguayense* (N.E.Br.) E. Walther. Two substrate mixtures were used: tezontle (3–4 mm) with peat (2:1) and tezontle (4–6 mm) with peat (2:1), with suction heights of 8 and 15 cm (H8 and H15). The results showed significant statistical differences ($p < 0.05$) in cumulative water consumption, suction height, and plant type. The ornamental species showed significant statistical differences in terms of water consumption (daily and cumulative), plant height, cover, and total fresh and dry matter production, where *D. ecklonis* recorded the highest values, while *G. paraguayense* maintained higher substrate moisture. These findings show that suction irrigation is an efficient water supply option in green infrastructure systems because water consumption is self-regulating.

Keywords: porous capsules, water use efficiency, self-supply, naturation, substrates.

INTRODUCTION

Freshwater resources are increasingly scarce, and their availability is under growing pressure from population growth, urbanization, and climate change (van Iersel *et al.*, 2016). Agriculture, which includes ornamental horticulture, is the main consumer of water resources globally, accounting for nearly 80 % of total use (Velasco-Muñoz *et al.*, 2018). The ornamental horticulture industry is on the rise, requiring the implementation of strategies to use water efficiently and minimize its environmental impact (van Iersel *et al.*, 2016). Ornamental production in Mexico before 1994 relied mainly on rainfed agriculture. After that year, the number of ornamental species cultivated under irrigation increased to more than 58, while in rainfed systems, the number rose only from 28 to 32 (LaFevor, 2022). Therefore, research and adoption of irrigation systems that promote efficient water use are indispensable.

Suction irrigation using ceramic porous emitters, commonly applied in small-scale vegetable production in arid regions, also has potential for ornamental plant cultivation (Peña-Casadevalls and Vargas-Rodríguez, 2018). The shapes of ceramic porous emitters are diverse. Early models were shaped as pans, pots (Cai *et al.*, 2018) and cylinders but changed to spheres. Olguín-Palacios (1975) used truncated cone-shaped emitters made of brick-colored clay with a capacity of 300 cm^3. In contrast, Quevedo-Nolasco *et al.* (2023) used spherical emitters of white kaolinite ceramic, connected to the water source by a 5 mm internal diameter flexible plastic tube, and operated under suction. Zhang *et al.* (2009) tested cylindrical ceramic emitters with dimensions of 15 cm in length, 4 cm external radius, and 3 cm internal radius, a saturated hydraulic conductivity of 0.012 cm d^{-1}, and operation under both positive and negative pressure. Similarly, Liu *et al.* (2023a) worked with cylindrical white clay emitters with a 1 cm internal radius, a 2 cm external radius, and a 7 cm length, operated at hydraulic loads ranging from 0 to 100 cm. Cai *et al.* (2021) also used cylindrical white clay emitters but with dimensions of 7 cm length, 4 cm external radius, and 2 cm internal radius.

Currently, porous emitters are typically buried, leading some researchers to classify them as a form of subirrigation (Cai *et al.*, 2018). Subsurface irrigation with ceramic emitters provides a continuous supply of water and nutrients at a constant low rate that maintains soil moisture and reduces evaporative water losses (Liu *et al.*, 2023b). Subsurface irrigation has economic and ecological advantages compared to surface irrigation, such as savings in labor, energy, water, and nutrients, as well as having more uniform plant growth, lower air humidity, fewer foliar diseases, and fewer environmental problems due to nutrient and chemical leaching (Qiaosheng *et al.*, 2007).

Irrigation with porous emitters is performed with both positive and negative charges (suction) (Olguín-Palacios, 1975; Zhang *et al.*, 2009). The water output of porous emitters used in suction irrigation depends on the size and pore percentage of the emitter and its surface, in addition to the height from which the water is absorbed, the suction gradient generated (depending on the evapotranspirative demand and soil type), and the thermal and osmotic gradient (Olguín-Palacios, 1975).

Irrigation with porous emitters is used in the production of crops such as tomato, goji berry, apple, bean, strawberry, corn, ornamental plants (geranium, petunia, and gazania), and pitahaya, among others. However, its application in ornamental horticulture is poorly documented. Therefore, the objective of this work was to analyze the water consumption of two species of ornamental plants by suction irrigation in two substrates and two suction heights, in pots. The effects of suction height (H), substrate type (S), and plant species (P) on response variables, including daily and cumulative water consumption as well as biophysical traits, were evaluated using a split-plot design in randomized blocks, under the hypothesis that at least one factor influences water consumption in the studied species.

MATERIALS AND METHODS

The experiment was carried out in a greenhouse at the Postgraduate College Campus Montecillo, in Texcoco, State of Mexico (19° 27′ 37.1′′ N and 98° 54′ 12.12′′ W), at an altitude of 2240 m, where the climate is semi-dry temperate with summer rains. The species assessment period was from May 9 to July 27, 2023.

An experimental design with plots subdivided into randomized blocks was established. Suction heights of 8 and 15 cm (H8 and H15, respectively) were measured in the large plot, substrate combination (S) in the medium plot, and plant type (P) in the small plot. The suction height represents the difference in level between the center of the capsule and the water level of the source. The substrate mixture consisted of tezontle and peat in a 2:1 (v/v) ratio. A coarse substrate (Sg) with tezontle particle diameters between 4 and 6 mm and a fine substrate (Sf) with tezontle particle diameters between 3 and 4 mm were used. The plants (P) were used *Dimorphotheca ecklonis* DC. (Pd) and *Graptopetalum paraguayense* (N.E.Br.) E. Walther (Pg). A total of eight treatments (2H × 2S × 2P) and four replicates were used, giving a total of 32 experimental units. Each pot was used as an experimental unit, which had a volume of 6 L (23.5 cm top diameter and 20 cm height) and a porous emitter (capsule) substrate-plant with storage as a water source.

The suction irrigation system consisted of a porous kaolinite capsule, 12 cm in diameter, equipped with two opposing tubes of 4 mm internal diameter. One tube was used to fill the capsule and subsequently sealed, while the other was connected to the water source (Figure 1). To evaluate the ability of the emitters to yield water, a sorptivity analysis was performed according to the methodology of Quevedo-Nolasco *et al.* (2023). This irrigation system does not require an external source of energy but takes advantage of the suction gradient, or differences in water matrix potential, that operates between a continuously dried soil due to the evapotranspiration of a crop and a porous body communicated with the water source, which allows a continuous, efficient, and localized supply only in the crop root zone (Olguín-Palacios, 1975). In order to differentiate each mixture, the water retention curve (de Boodt *et al.*, 1974) and bulk density were determined at the Soil Physics Laboratory of the Postgraduate College.

Graptopetalum paraguayense, commonly known as mother-of-pearl or ghost plant, is a Mexican species of the Crassulaceae family. Its rosettes reach 15–20 cm in diameter, and it exhibits crassulacean acid metabolism (CAM). In addition to its ornamental use, it is used medicinallly for liver disorders, diuretic effects, diabetes, hypertension, and pain relief in China (Ai *et al.*, 2017). *Dimorphotheca ecklonis* (Cape daisy or polar star)

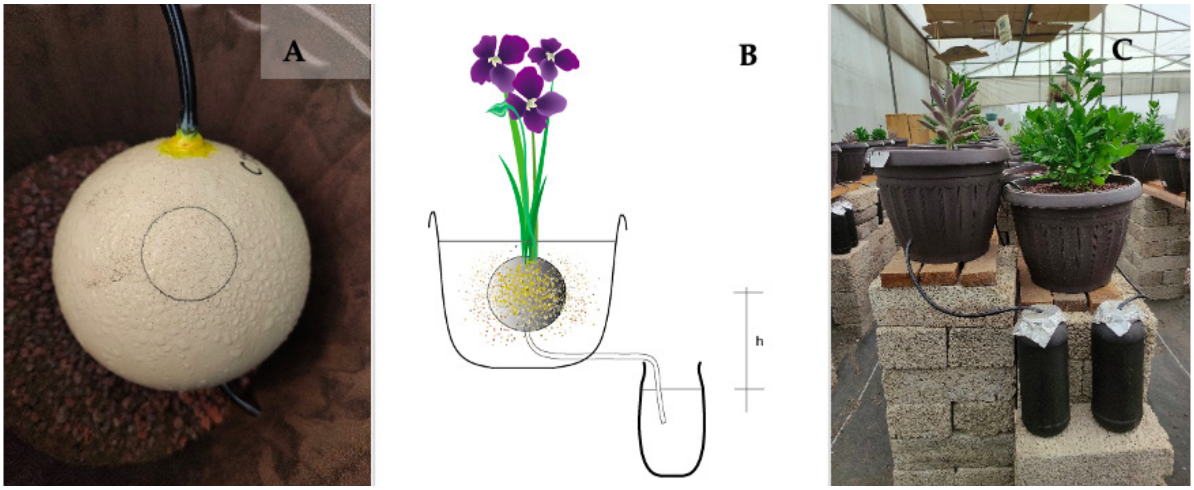

Figure 1. Suction irrigation system used for the evaluation of water consumption. A: porous capsule releasing water; B: suction irrigation scheme with porous emitter; C: suction irrigation on ornamental species.

is an ornamental African species of the Asteraceae family with abundant white, pink, purple, or salmon flowers measuring 5–8 cm (Khalil and Seleem, 2019). These plants were selected for their availability in nurseries, size, low maintenance requirements, and adaptability to the climate of the evaluation site. Prior to transplanting, both were acclimatized in the greenhouse for three weeks, reaching average heights of 7 cm and 6 cm and diameters of 8.5 cm and 6 cm, respectively.

Well water (pH 6.9 and electrical conductivity of 276 mS cm^{-1}) was used as the base for preparing the nutrient solution, following the formulation of Steiner (1984). The solution had an electrical conductivity of 0.5 dS m^{-1}, with 3 NO_3^-, 0.25 $H_2PO_4^-$, 1.75 SO_4^{2-}, 1.75 K^+, 2.25 Ca^{2+}, and 1 Mg^{2+} milliequivalents per liter (mEq L^{-1}) and an osmotic pressure of 0.018 MPa. The following nutrient sources were used: calcium nitrate ($Ca(NO_3)_2$), potassium nitrate (KNO_3), monopotassium phosphate (KH_2PO_4), potassium sulfate (K_2SO_4), magnesium sulfate ($MgSO_4$), and sulfuric acid (H_2SO_4), in addition to micronutrients (Rovensa Next, Mexico), with iron (Fe^{2+}), manganese (Mn^{2+}), zinc (Zn^{2+}), boron (H_3BO_3), copper (Cu^{2+}), and molybdenum (MoO_4^{2-}). The nutrient solution was placed in a 1.1 L black container with a lid to avoid algae proliferation.

During the experiment, daily water consumption (DWC) was measured, which started on May 9 by adding the volume consumed on the previous day by means of a test tube at 8:00 am. Daily consumption was transformed to daily irrigation lamina by dividing the daily water consumption (cm^3) by the exposed area of the pot (430 cm^2). The daily water consumptions were summed to obtain the cumulative water consumption (CWC). Moisture variations in the substrates were recorded and calculated using the gravimetric method at a distance of 2 cm from the emitter.

Daily evaporation was measured using a tub placed inside the greenhouse. In addition, plant height (cm), canopy cover (%), and substrate volumetric moisture content (v/v) were recorded weekly. Volumetric moisture represents the ratio of water volume to soil volume and is dimensionless. Moisture was calculated by the gravimetric method from the start of the experiment until July 5. To avoid damage to the roots of *D. ecklonis*, samples of 40 cm^3 of substrate were obtained at a distance of 1.5 cm from the capsule. At the end of the experiment, on July 27, 2023, total fresh matter (TFM) was measured by destructive sampling (aerial and root biomass) and total dry matter (TDM). Additionally, water use efficiency (WUE) was calculated by dividing TDM by the cumulative water consumption in lamina.

Analysis of variance (ANOVA) was performed for response variables ($p < 0.05$). The assumptions of normality of residuals were examined with the Shapiro-Wilk test ($p > 0.05$). Data independence was analyzed graphically, and for homogeneity of variances, Bartlett's test was used ($p > 0.01$). When significant differences between means were found, Tukey's test was performed. Statistical analysis was performed with the RStudio program (R Core Team, 2024).

RESULTS AND DISCUSSION

Characteristics of the porous capsules and substrates

The sorptivity values of the porous capsules had a mean of 0.576 mm $s^{-1/2}$, a standard deviation of 0.033, and 5.71 % coefficient of variation. As for the substrates, the bulk density was 0.59 g cm^{-3} for Sf and 0.56 g cm^{-3} for Sg. On water retention, the fine substrate (Sf) retained slightly more water compared to the coarse substrate (Sg) at water column suction heights of 0, 10, and 50 cm (Table 1). Also, Sf presented greater pore space, aeration capacity, readily available water, and reserve water.

Table 1. Volumetric water content of fine (Sf) and coarse (Sg) substrates at different suction (water column) values.

Suction (CCA)	Fine substrate (v/v)	Coarse substrate (v/v)
0	0.49	0.38
10	0.22	0.14
50	0.16	0.11
100	0.09	0.09

CCA: centimeters of water column; v/v: volumetric moisture content (dimensionless). Fine substrate (Sf) consisted of tezontle (3–4 mm) mixed with peat (2:1), and coarse substrate (Sg) consisted of tezontle (4–6 mm) mixed with peat (2:1).

Water release capacity of the porous capsules

The volume of water released to suction varied between 21 and 442 mL d^{-1}, with a mean of 110 mL d^{-1}, which depended on several factors such as the hydraulic characteristics of the emitters, including suction height, crop, and environmental conditions (Quevedo-Nolasco *et al.*, 2023). In tomato with suction irrigation, Vargas-Rodríguez *et al.* (2010) reported irrigation doses between 180 and 390 mL d^{-1} plant^{-1}. Similarly, Peña-Casadevalls and Vargas-Rodríguez (2018) reported water consumptions between 200 and 330 mL d^{-1}. Although the operating conditions, type of crop, environment, porous media, and suction height are not the same, it should be emphasized that the suction irrigation system meets the water demand.

Several irrigation systems operate using porous emitters. Abu-Zreig *et al.* (2006) found leakage rates of 125–1020 mL d^{-1} operating at positive pressure in an irrigation system with porous pots (pitchers). Liu *et al.* (2023b) observed irrigation laminae below 5 mm d^{-1} in a tomato crop irrigated with porous emitters operating at positive hydraulic loads between 0.1 and 0.5 m. Unlike these systems, suction irrigation allows precise control of water delivery, providing water exactly when needed and minimizing losses due to infiltration.

Daily water consumption by factors

In the experimental units, lamina water consumption varied between 1 and 8 mm d^{-1}, with a behavior similar to water evaporation that depends on atmospheric weather elements. The suction heights of 15 and 8 cm (H15 and H8, respectively) and plant species (Pg and Pd) factors influenced water consumption (Figures 2A and 2C). However, the substrate (Sg and Sf) had no effect (Figure 2B), so despite minor variations in terms of water retention, there were no significant differences.

Daily water consumption varied between 1.7 and 5.5 mm (mean 3 mm) at a suction height of 8 cm and between 1.1 and 3.7 mm (mean 2.1 mm) at 15 cm. By substrate, the coarse substrate (Sg) averaged 2.6 mm (1.5–5.5 mm), while the fine substrate (Sf) averaged 2.5 mm (1.1–4.2 mm). For plant species, Pg consumed 1.1–2.3 mm and Pd 2.2–5.5 mm, with a mean of 1.7 and 3.4 mm, respectively.

Cumulative water consumption by factors

At the end of the experiment, the established species had a water consumption of 236.7 mm at 8 cm suction height compared to 170.9 mm obtained at 15 cm due to less force to recover water from the source and lower negative pressure (Figure 2D). In irrigation with porous emitters, the applied hydraulic load determines the amount of water available to the soil, plant, and atmospheric system (Liu *et al.*, 2023a). In this type of irrigation, ceramic porous emitters operate both at negative pressure or suction (Olguín Palacios, 1975; Quevedo-Nolasco *et al.*, 2023) and positive pressure (Liu *et al.*, 2023b).

Cumulative water consumption per substrate was similar, with values of 198.7 mm for Sf and 208.9 mm for Sg (Figure 2E). This should be interpreted with caution, since water

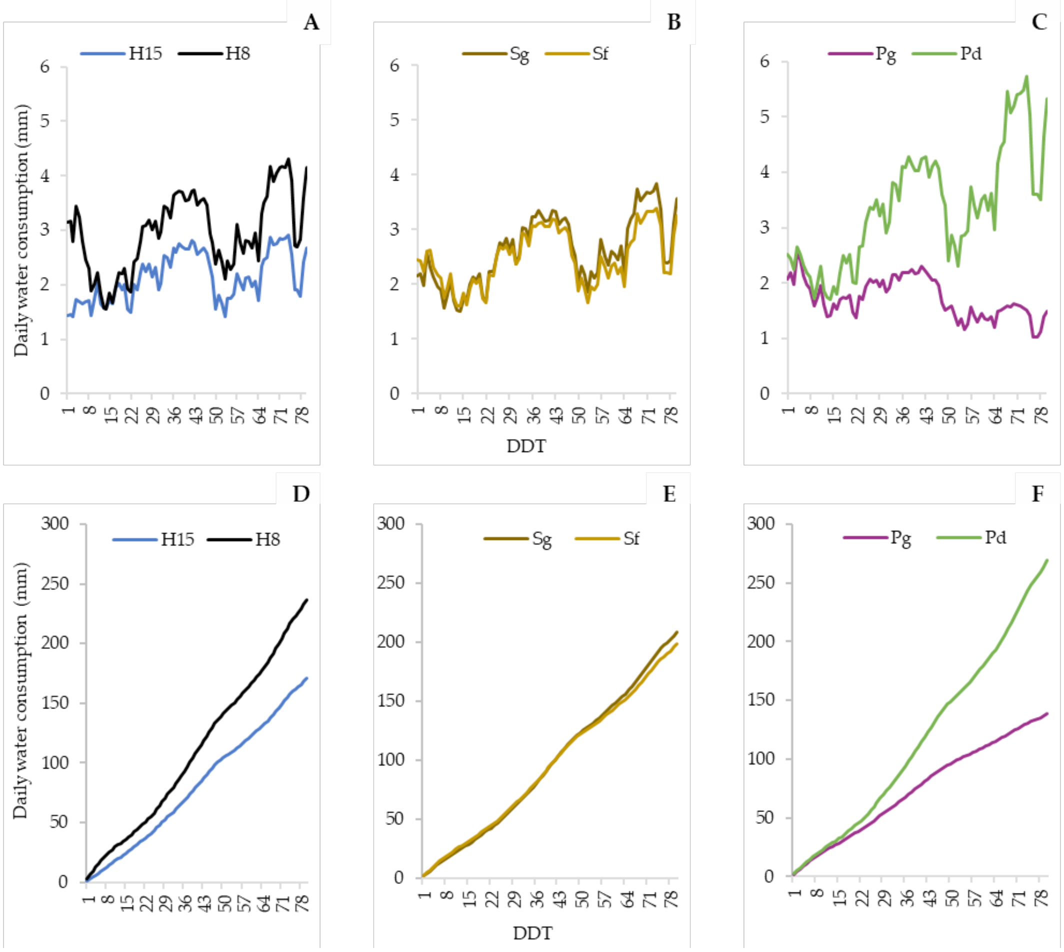

Figure 2. Daily (A–C) and accumulated (D–F) water consumption of ornamental species under suction irrigation, showing effects of suction height (H15, H8), substrate type (Sg, Sf), and plant species (Pg, Pd). H15: suction height of 15 cm; H8: suction height of 8 cm; Sg: tezontle (4–6 mm)-peat 2:1 (v/v); Sf: tezontle (3–4 mm)-peat 2:1 (v/v); Pg: *Graptopetalum paraguayense* (N.E.Br.) E. Walther; Pd: *Dimorphotheca ecklonis* DC.; DDT: days after transplanting.

movement in soil (or growth medium) is influenced by its physical characteristics (Ma *et al.*, 2022), where differences between substrates in terms of water retention were minimal (Table 2).

In terms of plant type, the cumulative water consumption of *D. ecklonis* and *G. paraguayense* was 269.4 and 138.2 mm, respectively (Figure 2F). The difference in cumulative water consumption is consistent with FAO (2006), which indicates that different species can have different levels of evapotranspiration, even under the same environmental conditions, due to differences in transpiration resistance, height, foliage roughness, albedo, orientation, soil cover, and root characteristics.

Table 2. Volumetric distribution of water, air, and solids in fine (Sf) and coarse (Sg) substrates composed of tezontle-peat mixtures (de Boodt *et al.*, 1974).

Variable	Sf (v/v)	Sg (v/v)
Solid material	0.51	0.62
Total pore space	0.49	0.38
Aeration capacity	0.28	0.25
Water readily available	0.06	0.03
Reserve water	0.06	0.02
Water hardly available	0.09	0.08

/v: volumetric content (dimensionless). Fine substrate (Sf): tezontle 3–4 mm + peat 2:1 (v/v); Coarse substrate (Sg): tezontle 4–6 mm + peat 2:1 (v/v).

Daily and cumulative water consumption by treatment

In the first 10 d after transplanting, the daily water consumption of all treatments depended on the suction height. The lower the height (lower negative pressure), the higher the water consumption and vice versa (Figure 3A), which was statistically validated. Seedlings acclimatized during the early stages, but as transpiration increased, so did water consumption. This period of increased water consumption during the first days of the establishment of the porous capsule irrigation system was also observed by Liu *et al.* (2023b) in a tomato crop irrigated with positive pressure porous emitters.

Treatments with *D. ecklonis* (Pg), regardless of substrate particle size and suction height, consumed a greater amount of water compared to *G. paraguayense* (Pd). As noticed by Durhman *et al.* (2007) and Khalil and Seleem (2019), both species exhibit distinct morphological and physiological characteristics. In particular, *D. ecklonis* showed faster growth than *G. paraguayense*, which was reflected in a higher water demand.

The average cumulative water consumption (expressed in mm) per treatment, in descending order, was as follows: H8SgPd (348), H8SfPd (286.9), H15SfPd (234.3), H15SgPd (208.2), H8SgPg (156), H8SfPg (155.8), H15SgPg (123.1), and H15SfPg (117.8) (Figure 3B). These water consumption values are comparable with those reported by Yang *et al.* (2024), who documented water consumptions between 300 and 450 mm in tomato crops irrigated with porous emitters at a pressure of 20 cm. Similarly, Liu *et al.* (2023a), also employing porous emitters, observed water consumptions of 85 and 110 mm in open-grown goji bushes under pressures of 40 and 80 cm, respectively, which also took advantage of a cumulative rainfall of 269.1 mm.

Substrate moisture

The volumetric moisture ratio (v/v) in the substrates remained between 0.09 and 0.19, with maximum moisture retention values of 0.38 and 0.49 for Sg and Sf, respectively.

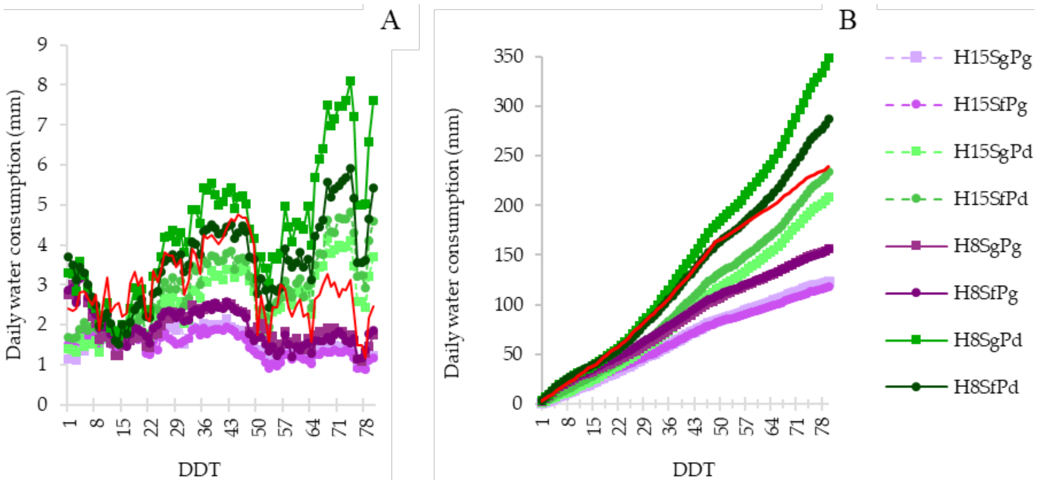

Figure 3. Daily (A) and cumulative (B) water consumption of treatments as influenced by suction height, substrate, and plant species. H15: suction height of 15 cm; H8: suction height of 8 cm; Sg: tezontle (4-6 mm)-peat mixture 2:1 (v/v); Sf: tezontle (3-4 mm)-peat mixture 2:1 (v/v); Pg: *Graptopetalum paraguayense* (N.E.Br.) E. Walther; Pd: *Dimorphotheca ecklonis* DC; DDT: days after transplanting.

The distribution of moisture in the substrate depends, in part, on the location of the sampling point in relation to the emitter, since more distance, both vertically and horizontally, results in a decrease in moisture content (Siyal *et al*., 2009). This peripheral distribution of water around the emitter is influenced by the particle size of the substrate and the water demand of the crop.

In previous studies, Zhang *et al.* (2009) reported volumetric soil moisture values of up to 0.43 at depths of 30–40 cm when using suction irrigation (30–50 cm) with porous emitters buried at a 20 cm depth; however, this moisture decreased over the course of days. Similarly, Liu *et al.* (2023b) observed soil moisture values between 0.17 and 0.22 when using porous emitters with pressures from 10 to 50 cm in tomato crops.

Suction height

Higher water uptake was observed at lower suction height (8 cm), registering a value of 236.7 ± 95 mm in H8 versus 170.9 ± 59.4 mm in H15. This uptake was inversely proportional to moisture content in the substrates, which was also higher at lower suction height (H8: 18.8 ± 2.5) compared to H15 (16.3 ± 2.6). The higher water availability in H8 allowed for superior plant development, evidenced by higher plant height, cover, total fresh matter, and total dry matter (Table 3). These results coincide with those reported by Ma *et al.* (2022), who emphasize that water availability directly influences the morphological and physiological characteristics of plants.

Table 3. Effects of suction height, substrate, and plant species on water consumption, substrate moisture, and evaluated plant growth variables.

Factors	DWC	CWC	Substrate moisture	Plant height	Soil cover	TFM	TDM	WUE
	(mm d^{-1})	(mm)	(v/v)	(cm)	(%)	(g)	(g)	(g TDM cm^{-1} H_2O)
H8	3.0 ± 0.7^{a}	236.7 ± 95^{a}	18.8 ± 2.5^{a}	17.8 ± 8.8^{a}	48.7 ± 43.3^{a}	193.6 ± 111.2^{a}	31.9 ± 27.7^{a}	1.1 ± 0.7^{a}
H15	2.1 ± 1.2^{b}	170.9 ± 59.4^{b}	16.3 ± 2.6^{b}	14.1± 5.0^{b}	34.0 ± 21.1^{b}	139.4 ± 48^{b}	17.7 ± 11.9^{b}	0.9 ± 0.4^{a}
p-value	0.0006	0.0006	0.028	0.0343	0.0305	0.028	0.0018	0.1846
Sg	2.6 ± 0.9^{a}	208.8 ± 23.8^{a}	18.4 ± 2.5^{a}	16.1 ± 8.3^{a}	47.8 ± 42.8^{a}	175.3 ± 99.7^{a}	27.1 ± 25.6^{a}	1.1 ± 0.6^{a}
Sf	2.5 ± 1.2^{a}	198.7 ± 76^{a}	16.8 ± 2.9^{a}	15.8 ± 6.3^{a}	34.9 ± 22.7^{a}	157.8 ± 78.3^{a}	22.5 ± 18.7^{a}	1.0 ± 0.5^{a}
p-value	0.4977	0.4977	0.1272	0.8123	0.052	0.4348	0.2249	0.4482
Pd	3.4 ± 0.3^{a}	269.9 ± 71.3^{a}	16.3 ± 2.5^{b}	21.0 ± 7.2^{a}	66.0 ± 33.8^{a}	220.3 ± 96.6^{a}	41.4 ± 20.5^{a}	1.5 ± 0.5^{a}
Pg	1.7 ± 0.9^{b}	138.2 ± 24.6^{b}	18.8 ± 2.6^{a}	10.9 ± 1.7^{b}	16.7 ± 2.4^{b}	112.7 ± 27^{b}	8.2 ± 2.3^{b}	0.6 ± 0.2^{b}
p-value	<0.0001	<0.0001	0.0235	<0.0001	<0.0001	0.0003	<0.0001	<0.0001

Values indicate mean ± standard deviation. Different letters represent significant differences (Tukey, $p < 0.05$). DWC: daily water consumption; CWC: cumulative water consumption; TFM: total fresh matter; TDM: total dry matter; WUE: water use efficiency; H15: suction height of 15 cm; H8: suction height of 8 cm; Sg: tezontle (4–6 mm)-peat mixture 2:1 (v/v); Sf: tezontle (3–4 mm)-peat mixture 2:1 (v/v); Pg: *Graptopetalum paraguayense* (N.E.Br.) E. Walther; Pd: *Dimorphotheca ecklonis* DC.

In this context, several authors have recommended the use of positive pressure with ceramic emitters for crop production in intensive farming systems. Pressure loads of 30, 40, and 70 cm (Liu *et al.*, 2023c), as well as ranges between 20 and 50 cm (Cai *et al.*, 2018), have been proposed. When applying pressurized water, the irrigation supply depends on both the hydraulic load and the operation mode of the system. Self-regulation of water supply in these systems is based on the hydraulic characteristics of the emitter, substrate type, emitter size, shape, and suction height, as well as the water requirements of the crop and environmental conditions.

Substrates

No significant differences were detected between substrates (S) in total daily water consumption or in the other variables analyzed. The retention of readily available water was 0.06 and 0.03 (v/v) for the respective substrates, according to Tukey's test. However, previous studies have reported contrasting findings. For example, Quevedo-Nolasco *et al*. (2023) observed substrate-related differences in water consumption using Duncan's test. Similarly, Wang *et al*. (2019) indicated that the physical characteristics of soils or growth media affect water movement, where the matrix suction influences water availability and, consequently, plant development. In line with this, Pacheco-Hernández *et al*. (2016) reported significant differences in height, leaf area, and dry matter in poinsettia cultivated in different substrate mixtures under suction irrigation.

Likewise, A'saf *et al*. (2020) documented variations in morphology, physiology, growth, and flower quality in three ornamental species grown across six substrate combinations.

Ornamental species

Both plant species presented significant differences in daily water consumption (CAD), cumulative water consumption (CWC), substrate moisture, plant height, cover, total fresh matter (TFM), total dry matter (TDM), and water use efficiency (WUE). In general, the highest values were recorded in *D. ecklonis*, with the exception of substrate moisture. Similarly, Quevedo-Nolasco *et al.* (2023) reported differences in cumulative water consumption in three ornamental species (gazania, petunia, and geranium) under suction irrigation for 80 days, with values ranging from 11.2 to 18.6 cm. These results highlight how different species can present differentiated patterns of water consumption depending on their specific characteristics.

Efficient use of water

No significant differences in water use efficiency (WUE) were found in relation to the suction height (H) of the emitters, registering values of 0.9 and 1.1 g TDM cm^{-1} H_2O for suction heights of 8 and 15 cm, respectively. Similarly, substrate type (S) did not show significant differences in terms of WUE, with values of 1.1 and 1.0 g TDM cm^{-1} H_2O for coarse (Sg) and fine (Sf) substrates, respectively. In contrast, significant differences were indeed observed as a function of species type (P), with WUE values of 1.5 and 0.6 g TDM cm^{-1} H_2O for *G. paraguayense* and *D. ecklonis*, respectively. This difference is congruent with the phenological and genomic differences existing between both species.

The study of water use efficiency in ornamental plants by suction irrigation with porous emitters is still limited. Zhang *et al.* (2009), in an experiment conducted with tomato crop, evaluated irrigation with porous emitters at different pressures (0, -30, and -50 cm H_2O column). The results showed that WUE was inversely proportional to yield. At a pressure of 0 cm H_2O, the highest yield was obtained, with 1.17 kg per pot and WUE of 24.9 kg m^{-3}, while at -50 cm H_2O, the lowest yield was recorded, with 0.95 kg per pot and WUE of 32.8 kg m^{-3}. Similar results were observed in greenhouses in Israel and Spain, where AD values between 25 and 33 kg m^{-3} of tomato (30–40 L kg^{-1}) were reported (Salazar-Moreno *et al*., 2014). These findings indicate that the suction irrigation system can change both WUE and yield depending on the suction height, substrate type, and, possibly, plant species grown.

In contrast, under pressure subirrigation conditions with porous emitters, Liu *et al.* (2023a) evaluated Goji berry production, finding WUE values of 1, 1.01, and 0.85 kg m^{-3} for pressure loads of 40, 60, and 80 cm, respectively. These results show how variations in irrigation pressure can influence water use efficiency, depending on the management of the system. Suction irrigation has the advantage of self-regulation of water from ceramic emitters, which represents a beneficial potential in terms of water efficiency.

CONCLUSIONS

Statistically significant differences were found in relation to suction height, understood as the difference between the source and the centroid of the irrigation emitter. At lower heights, the highest values were achieved in daily and cumulative water consumption, substrate moisture, plant height, coverage, total fresh matter, and total dry matter. No statistically significant differences were identified between substrate mixtures, probably due to the minimal differences in their physical characteristics (particle size), which are related to water retention.

Among the ornamental species evaluated, statistically significant differences were found in the parameters of daily and cumulative water consumption, height, coverage, and total fresh and dry matter production. *Dimorphotheca ecklonis* showed the highest values for these parameters, while *G. paraguayense* showed a higher level of moisture in the substrate. Both the objective and the hypothesis were validated, demonstrating that the factors of suction height and type of ornamental species significantly influenced the response variables evaluated.

ACKNOWLEDGEMENTS

To the Secretariat of Science, Humanities, Technology, and Innovation (SECIHTI) for awarding M.N.N.F. a scholarship to further his studies and research, as well as to the Postgraduate College Montecillo Campus, Postgraduate Program in Hydro Sciences.

REFERENCES

A'saf TS, Al-Ajlouni MG, Ayad JY, Othman YA, St. Hilaire R. 2020. Performance of six different soilless green roof substrates for the Mediterranean region. Science of the Total Environment 730: 139182. https://doi.org/10.1016/j.scitotenv.2020.139182

Abu-Zreig MM, Abe Y, Isoda H. 2006. The auto-regulative capability of pitcher irrigation system. Agricultural Water Management 85 (3): 272–278. https://doi.org/10.1016/j.agwat.2006.05.002

Ai L, Chung YC, Jeng KCG, Lai PFH, Yeh SC, Lee KC, Lin SY, Xia Y, Wang G, Cui SW. 2017. Antioxidant hydrocolloids from herb *Graptopetalum paraguayense* leaves show anti-colon cancer cells and anti-neuroinflammatory potentials. Food Hydrocolloids 73: 51–59. https://doi.org/10.1016/j.foodhyd.2017.06.027

Cai Y, Wu P, Zhang L, Zhu D, Wu S, Zhao X, Chen J, Dong Z. 2018. Prediction of flow characteristics and risk assessment of deep percolation by ceramic emitters in loam. Journal of Hydrology 566: 901–909. https://doi.org/10.1016/j.jhydrol.2018.07.076

Cai Y, Wu P, Zhu D, Zhang L, Zhao X, Gao X, Ge M, Song X, Wu Y, Dai Z. 2021. Subsurface irrigation with ceramic emitters: An effective method to improve apple yield and irrigation water use efficiency in the semiarid Loess Plateau. Agriculture, Ecosystems and Environment 313: 107404. https://doi.org/10.1016/j.agee.2021.107404

De Boodt M, Verdonck O, Cappaert I. 1974. Method for measuring the water release curve of organic substrates. Acta Horticulturae 37: 2054–2063. https://doi.org/10.17660/actahortic.1974.37.20

Durhman AK, Rowe DB, Rugh CL. 2007. Effect of substrate depth on initial growth, coverage, and survival of 25 succulent green roof plant taxa. HortScience 42 (3): 588–595. https://doi.org/10.21273/hortsci.42.3.588

FAO (Food and Agriculture Organization). 2006. Evapotranspiración del cultivo. Guías para la determinación de los requerimientos de agua de los cultivos. Estudios FAO Riego y Drenaje 56. Roma, Italia. http://www.fao.org/3/x0490s/x0490s00.htm (Retrieved: December 2023).

Khalil SE, Seleem FM. 2019. Role of biochar soil amendment for alleviation of adverse effects of water stress on *Dimorphotheca ecklonis* plants. Bioscience Research 16 (2): 1337–1353.

LaFevor MC. 2022. Spatial and temporal changes in crop species production diversity in Mexico (1980–2020). Agriculture 12 (7): 985 https://doi.org/10.3390/agriculture12070985

Liu X, Han M, Zhang L. 2023a. A new subsurface ceramic emitter for smallholders without pumps: design, hydraulic performance, and field application. Irrigation Science 41 (6): 835–845. https://doi.org/10.1007/s00271-023-00877-4

Liu X, Zhang L, Liu Q, Yang F, Han M, Yao S. 2023b. Subsurface irrigation with ceramic emitters: optimal working water head improves yield, fruit quality and water productivity of greenhouse tomato. Scientia Horticulturae 310: 111712. https://doi.org/10.1016/j.scienta.2022.111712

Liu X, Zhang L, Zhang C, Sun Y, Yang X. 2023c. Optimization algorithm for determining working water head of subsurface irrigation with ceramic emitters based on soil wetting patterns. Computers and Electronics in Agriculture 212: 108069. https://doi.org/10.1016/j.compag.2023.108069

Ma Y, Liu H, Yu Y, Guo L, Zhao W, Yetemen O. 2022. Revisiting soil water potential: Towards a better understanding of soil and plant interactions. Water 14 (22): 3721. https://doi.org/10.3390/w14223721

Olguín-Palacios, C. 1975. Suction irrigation; description of the method and advances in investigation. First drip irrigation seminar. Colegio de Postgraduados: Texcoco, Mexico.

Pacheco-Hernández P, López-Martínez V, Andrade-Rodríguez M, Alia-Tejacal I, de Jesús Sainz-Aispuro M, Villegas-Torres OG, Arteaga-Ramírez R, Vázquez-Peña MA. 2016. Cuantificación microlisimétrica del consumo de agua residual tratada en la nochebuena (*Euphorbia pulcherrima* Willd. ex Klotzsch). Tecnología y Ciencias del Agua 7 (6): 179–186.

Peña-Casadevalls MS, Vargas-Rodríguez P. 2018. Suction irrigation technology for the production of tomato (*Lycopersicon esculentum)* under controlled conditions. Revista Ciencias Técnicas Agropecuarias 27 (2).

Qiaosheng S, Zuoxin L, Zhenying W, Haijun L. 2007. Simulation of the soil wetting shape under porous pipe sub-irrigation using dimensional analysis. Irrigation and Drainage 56 (4): 389–398. https://doi.org/10.1002/ird.290

Quevedo-Nolasco A, Herrera-Gómez SS, Zamora-Morales BP, Rodríguez-Cruz E. 2023. Water consumption of three ornamental species with the suction irrigation system. Agro Productividad 16 (5): 3–15. https://doi.org/10.32854/agrop.v16i5.2354

R Core Team. 2024. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/

Salazar-Moreno R, Rojano-Aguilar A, López-Cruz IL. 2014. La eficiencia en el uso del agua en la agricultura controlada. Tecnología y Ciencias del Agua 5 (2): 177–183.

Siyal AA, van Genuchten MT, Skaggs TH. 2009. Performance of pitcher irrigation system. Soil Science 174 (6): 312–320. https://doi.org/10.1097/SS.0b013e3181a97532

Steiner AA. 1984. The universal nutrient solution. Proceedings of the Sixth International Congress on Soilless Culture: Wageningen, Netherlands, pp: 633–650.

van Iersel MW, Chappell MR, Thomas PA. 2016. Optimizing growth, quality, and profits through precision irrigation in ornamental plant production. Acta Horticulturae 1131: 57–64. https://doi.org/10.17660/ActaHortic.2016.1131.8

Vargas-Rodríguez P, Peña-Casadevalls M, García-Victoria K, Roble-de la Rosa D, Álvarez-Andión R. 2010. Sistema de riego con emisores porosos para la producción de tomate con ahorro de agua y energía: propuesta de diseño. Ingeniería Hidráulica y Ambiental 31 (1): 34–42.

Velasco-Muñoz JF, Aznar-Sánchez JA, Belmonte-Ureña LJ, Román-Sánchez IM. 2018. Sustainable water use in agriculture: A review of worldwide research. Sustainability 10 (4): 1084. https://doi.org/10.3390/su10041084

Wang JJ, Long HY, Huang YF, Wang XL, Cai B, Liu W. 2019. Effects of different irrigation management parameters on cumulative water supply under negative pressure irrigation. Agricultural Water Management 224: 105743. https://doi.org/10.1016/j.agwat.2019.105743

Yang F, Wu P, Zhang L, Wei Y, Tong X, Wang Z. 2024. Effects of subsurface irrigation types on root distribution, leaf photosynthetic characteristics, and yield of greenhouse tomato. Scientia Horticulturae 328: 112883. https://doi.org/10.1016/j.scienta.2024.112883

Zhang J, Saito H, Kato M. 2009. Study on subsurface irrigation using ceramic pitcher on tomato cultivation in greenhouse. Journal of Arid Land Studied 19 (1): 265–267.