Research article

# Effect of the irrigation system on the germination and initial root development of *Pinus engelmannii* Carrière

# Efecto del sistema de riego en la germinación y el desarrollo inicial de la raíz de *Pinus engelmannii* Carrière

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**Abstract**

In the production of containerized forest plants, irrigation systems are used that directly influence plant development. It is important to seek alternatives that ensure uniform distribution and efficient use of water. In this study, the water consumption of three irrigation systems was measured, and their effect on the germination and root development of *Pinus engelmannii* in a nursery was evaluated. The trial included three treatments: micro-sprinkler irrigation, manual irrigation, and subirrigation. Germination was monitored for 36 days, and the initial growth of the root system, as well as water consumption and moisture retention in the substrate, were measured in each system. The variables evaluated were: germination percentage and speed, cumulative germination, peak value, germination value, uniformity coefficient, and root system growth. The root system was analyzed using image analysis techniques with RhizoVision, which calculated the number of roots, root length, absorption surface area, and root volume. Germination rates above 80 % were obtained in all three treatments, with the highest rate observed in the micro-sprinkler system. Plants with subirrigation had greater length, surface area, and volume in the middle region of the container. Water usage in micro-sprinkling was 12 times that of sub-irrigation. The type of irrigation system influenced the germination and root development stage of *P. engelmannii*. With regard to water use, the subirrigation system was more efficient.

**Keywords:** Irrigation efficiency, seed emergence, micro-sprinkling, pine, subirrigation, forest nursery.

**Resumen**

En la producción de planta forestal en contenedor se emplean sistemas de riego que influyen directamente en el desarrollo de las plantas. Es importante buscar alternativas que garanticen una distribución uniforme y un aprovechamiento eficiente del agua. En el presente trabajo se midió el gasto de agua de tres sistemas de riego y se evaluó su efecto en la germinación y desarrollo radical de *Pinus engelmannii* en vivero. El ensayo incluyó tres tratamientos: riego por microaspersión, manual y por subirrigación. Se monitoreó la germinación durante 36 días, así como el crecimiento inicial del sistema radical y se midió el gasto de agua y la retención de humedad en el sustrato en cada sistema. Las variables evaluadas fueron: porcentaje y velocidad de germinación, germinación acumulada, valor pico, valor germinativo, coeficiente de uniformidad y crecimiento del sistema radical. El sistema radical se analizó mediante la técnica de análisis de imagen con el programa *RhizoVision*, en el cual se calculó el número de raíces, longitud, superficie de absorción y volumen. Se obtuvo una germinación superior a 80 % en los tres tratamientos, la más alta fue en el sistema de microaspersión. Las plantas con subirrigación tuvieron mayor longitud, superficie y volumen en la región media del envase. El gasto de agua en microaspersión superó 12 veces al de subirrigación. El tipo de sistema de riego influyó en la etapa de germinación y desarrollo radical de *P. engelmannii*. Respecto al uso del agua, el sistema de subirrigación fue más eficiente.

**Palabras clave:** Eficiencia del riego, emergencia de semilla, microaspersión, pino, subirrigación, vivero forestal.

# Introduction

The production of forest plants in nurseries must ensure an adequate water supply, in sufficient quantity and quality, to support optimal development throughout the entire growing cycle (Sánchez-Velázquez et al., 2023). However, ignorance of the water requirements of forest species and technical deficiencies in irrigation systems generally result in excessive water consumption (Dumroese et al., 1995). Irrigation water is the means by which fertilizers and other agrochemicals are applied to crops; however, any water that is not used by the plants is a source of contamination for the soil and water bodies surrounding the nursery (Dumroese et al., 2005). Within this context, and given the current challenges posed by water scarcity, it is essential to design, improve, and innovate technologies and processes to enhance the efficiency of irrigation systems in forest nurseries (de Carvalho et al., 2025).

In Mexico, the predominant forest-plant production system is carried out in containers, and most cultivated species belong to the *Pinus* L. genus (Comisión Nacional Forestal [Conafor], 2023). This diagram depicts various irrigation systems, the choice of which is

determined by factors such as species, substrate type, container size, installation costs, and maintenance requirements. However, in either case, irrigation effectiveness is an important consideration because the plant is confined within the container and has access to water only through this system (Cartes-Rodríguez et al., 2019). The choice of irrigation system and its maintenance are essential, as improper operation can cause damage or production losses (López-Martínez et al., 2014).

Irrigation management varies with the stage of plant development; initial seedling growth requires special attention, as optimal moisture conditions must be maintained for germination and early root system development. During the germination stage, micro-sprinkler or manual irrigation systems should be superficial and frequent, using fine droplets to prevent the seeds from being exposed and losing the moisture required for germination (Sánchez-Velázquez et al., 2023).

The subirrigation method is rarely used in forest plant production; this system allows water and nutrients to move upward through the substrate by capillary action from the bottom of the containers (Ferrarezi et al., 2015). Because it is a closed system, water and nutrients can be recirculated, reducing water use by 70 to 87 % (Ramírez-Galicia et al., 2022), and it represents a decisive advantage in the face of the current problem of water scarcity.

Nursery operators recognize the importance of water availability for forest tree cultivation; however, little attention is paid to the efficiency of the irrigation method or system used, particularly during the initial establishment stage, which is critical for ensuring successful production. Based on the above, the objective of this study was to evaluate water usage with three different irrigation systems —micro-sprinkler, subirrigation, and manual—, as well as their effect on the germination and root development of *Pinus engelmannii* Carrière in a nursery.

# Materials and Methods

## Study location and growing conditions

The study was conducted at the *Práxedis Guerrero* forest nursery, run by the Ministry of Natural Resources and the Environment (*Secretaría de Recursos Naturales y Medio Ambiente*, *SRNMA*) of the *Durango* State Government, Mexico, located in *Durango*, *Durango*, at 23°56'58.3" N and 104°34'07.4" W, and an altitude of 1 890 m.

The plants were grown in a tunnel greenhouse measuring 10.7 m in width by 56 m in length, with a height at the zenith of 4.4 m, covered with two layers: the lower layer consists of a black polyethylene shade cloth with 50 % light transmissivity, and the upper layer consists of a 720-gauge chlorophyll green plastic cover with ultraviolet protection and 80 % light transmissivity.

The seeds of *P. engelmannii* were collected from a seed stand located in the *La Mesa* property, in *Santa Isabel de Batres* town, *Durango* municipality, *Durango* state (24°11'47.75" N and 104°53'43.62" W), at 2 488 masl. The seeds were obtained in January 2016 and remained stored at 4 °C until use (cold room, model MTZ050-4 Danfoss® refrigeration equipment, Mexico). Black rigid polyethylene containers with root guides, measuring 4 cm in diameter at the top, 20.7 cm in length, and a capacity of 160 mL, were used. The containers were arranged in 98-cavity tube trays measuring 60.5 cm long and 31 cm wide. The substrate was a mixture of peat (50 %), vermiculite (25 %), and perlite (25 %), with a total porosity of 60.4 %, aeration porosity of 34.4 %, and a water retention capacity of 26 %.

Prior to sowing, the seeds were immersed in water at room temperature for 24 hours, with the water changed every 8 hours. Subsequently, Prozycar® 500 *F* carbendazim fungicide (Mexico) was applied to prevent fungal damage, and, finally, the seeds were

left to dry outdoors in the shade. Planting took place on July 30th, 2024. For this purpose, one seed per container was placed at a depth of 1 cm and covered with the same substrate. During the 36-day evaluation period, the average temperature and relative moisture were 21.6 °C and 61.5 %, respectively.

## Assessed irrigation systems

The experiment consisted of three completely randomized treatments corresponding to the three irrigation systems (aerial micro-sprinkler, manual irrigation, and subirrigation); each treatment consisted of three replicates, five trays with 98 cavities per replication in each irrigation system (Table 1, Figure 1); in total, 45 trays were used.

**Table 1.** Description of irrigation systems at the germination and initial development stages of *Pinus engelmannii* Carrière.

| Watering system | Components |
|---|---|
| Micro-sprinkler | Composed of primary (2" PVC) and secondary (½" polyethylene) pipes, from which tertiary (3 mm polyethylene) pipes are derived, supporting emitters with a spray radius of 3 m. |
| Manual | Composed of primary (2" PVC) piping, with a ¾" outlet valve to which a hose of the same size is connected, with a nozzle for a Melnor® spray head with shower head measuring 20.8×6.5 cm. |
| Subirrigation | 1 100 L water tank with 1 ¼" outlet pipe feeding tubs measuring 1.20 m in width by 3 m in length and 25 cm in height, which are placed on metal tables at a height of 95 cm. |
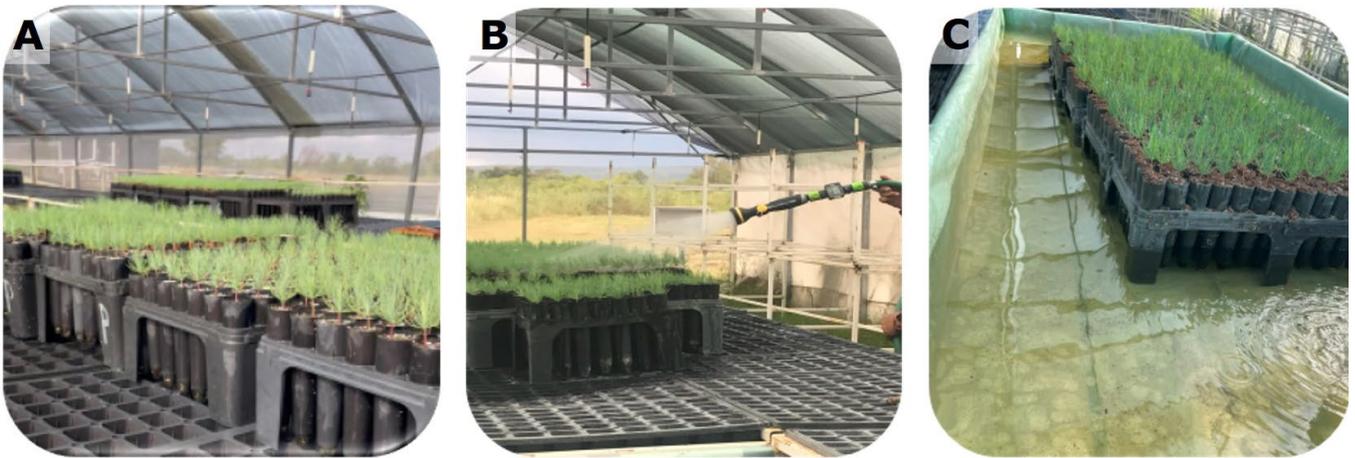
A = Micro-sprinkler system; B = Manual system; C = Subirrigation system.

**Figure 1.** Overview of irrigation systems evaluated at the germination and initial development stages of *Pinus engelmannii* Carrière.

The greenhouse was divided into three areas, each for a different type of irrigation system. The water came from a main tank with a capacity of 330 m³. Using a 3.5 HP hydraulic pump, the water was transported to the production structure through a 4" PVC main pipe equipped with slotted-ring filters.

## Water usage analysis

Water usage was recorded by irrigation system type, which was applied every other day for the micro-sprinkler and manual systems, while the subirrigation system was utilized twice a week; the duration of the irrigation was 45 minutes. Micro-sprinkling was carried out using a 2" electronic turbine flow meter (model OEM Ticfox®) attached to the greenhouse's main internal pipe; 20 % was subtracted from the total water record (including the area of aisles, headboards, and production tables) to account for non-productive spaces on the tables. Manual irrigation was performed using a

model ICS006-DLS Rainpoint® digital flow meter, installed at the end of the ¾" irrigation hose. For the subirrigation system, the reduction in the volume of water in the tank was measured directly each week using a model FH-5M Truper® tape measure. Subsequently, the volume formula for a cylinder was applied.

Water retention in the substrate was determined twice during the evaluation period. For this purpose, the trays were weighed dry on a model base-40P Pretul® scale prior to watering. Next, each system was watered as normal. After one hour, the new weight was recorded, and the difference between the two readings was calculated to estimate the volume of water retained in the substrate.

## Seed germination analysis

Seed germination and seedling emergence were evaluated every two days, starting from sowing, for 36 days. Seedling emergence was defined as the point at which the hypocotyl emerged above the substrate surface. The germination percentage (International Seed Testing Association [ISTA], 2015), $R_{50}$ (Coolbear et al., 1984), and germination rate (Bewley & Black, 1994), as well as the germination value (Czabator, 1962), peak value (Bonner, 1967), and uniformity coefficient (Bewley & Black, 1994) were determined.

## Root analysis

At the end of germination, when the plants reached 28 days of age, root analysis was performed, for which four plants per repetition were randomly selected. The substrate was removed by washing with water, and the roots were immediately scanned with a model T720DW Brother® scanner on a black background at 600 dpi. After completing digitization, full root images were split into three equal sections by dividing the container's 21-cm length into 7-cm upper, middle, and lower segments. Measurements taken for each section included total number of roots, root length, absorptive surface area, and volume, using RhizoVision Explorer® version 2.0.3 (Seethepalli et al., 2021).

## Statistical analysis

The data on germination parameters and root growth per section were analyzed using one-way ANOVA. For germination percentages and root counts, generalized linear models with binomial and Poisson distributions were fitted, respectively. When the effect of the irrigation system was significant, a Tukey's mean comparison test was performed at $a$=0.05. The assumptions of normality and homoscedasticity of the residuals were tested for all variables. When these assumptions were not met, the variable was transformed using the logarithmic function. Statistical analysis was performed using R software version 4.4.1 (R Core Team, 2024).

# Results and Discussion

## Water usage and retention

During the germination stage (36 days), the total expenditure of the three irrigation systems was 14 203 L; the difference between extreme values was 9 562 L; the system that saved the most water was subirrigation, while micro-sprinkling saved the least (Figure 2).

■ Subirrigation  ■ Manual  ■ Micro-sprinkler

876

2 889

10 438

**Water usage  (L)**
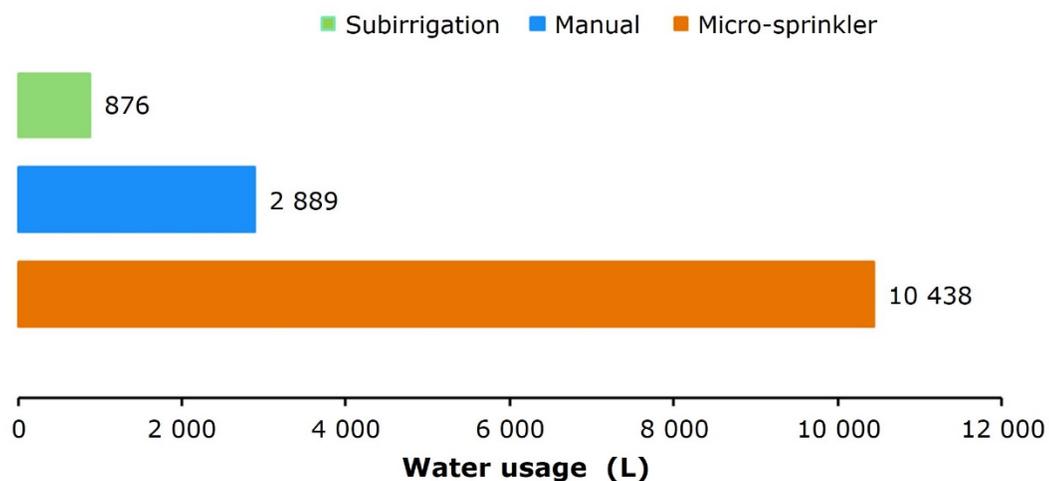
**Figure 2.** Volume of water consumed by each irrigation system over a 36 day period.

Water retention varied between systems, as did the number of irrigations applied. The substrate with manual irrigation retained the greatest water volume, whereas the substrate with micro-sprinkler irrigation retained the least; both received the same number of irrigations (Table 2). The differences in water retention between these systems can be attributed to the fact that in manual irrigation water is applied more intensely, so the porous spaces become saturated more quickly; in the micro-

sprinkler system, the intensity of irrigation is lower and slower, which causes the saturation of the porous spaces in the substrate to be slower; in addition, part of the water falls into dead spaces (Aldrete et al. 2024).

**Table 2.** Volume of water retained in each irrigation system.

| Treatment | Irrigations (No.) | Retention due to irrigation (L) | Total retention (L) |
|---|---|---|---|
| **Micro-sprinkler** | 16 | 22.1 | 353.6 |
| **Manual** | 16 | 29.5 | 472.0 |
| **Subirrigation** | 12 | 33.4 | 400.8 |

González-Torralva and López-López (2024) cited a total expenditure of 2 732 L for a subirrigation system for pine tree production, which surpassed the expenditure in this trial because they considered a longer period (8 months, not including the germination stage). On the other hand, water consumption in the subirrigation system was close to that reported by Ramírez-Galicia et al. (2022), who recorded consumption of 1 159 L at the initial stage of forest plant production. This difference may be due to the fact that the initial stage extends from planting to the final phase of establishment, approximately two to three months (Aldrete et al., 2023). According to López-López et al. (2023), the subirrigation system proved the most efficient; they found that the sprinkler/watering can system uses twice as much water as the subirrigation system. In this case, micro-sprinkler and manual irrigation used 12 and 4 times as much water, respectively, as subirrigation.

Water retention per plant is an important variable from the point of view of efficient use. During plant production, two to three irrigations per week were applied depending on prevailing weather conditions. The amount of water applied was determined according to the criterion of González-Alemán et al. (2025), who suggests maintaining moisture in at least the bottom two-thirds of the container to prevent restraining the root system growth. However, in the future, it would be interesting to

base the frequency and amount of water to be applied on the percentage of moisture in the substrate.

The substrate used in this study had a water retention capacity of 26 %; however, this value differed across the irrigation systems. In the case of subirrigation, the availability and distribution of water within the container were uniform throughout the irrigation period, which favored capillary movement. In the other two systems, the water volume was irregular, which affected water retention despite the use of the same substrate across all treatments. This aligns with the findings of Díaz-Blanco et al. (2025), who observed that the micro-sprinkler system does not result in uniform water distribution within the production area, and, therefore, the subirrigation system is a more efficient alternative.

## Germination

Emergence began on the eighth day after sowing (DAS); the maximum accumulation was reached at 26 days. The micro-sprinkler system showed the highest percentage (Table 3), with 50 % germination ($R_{50}$) at 10 days, with no significant differences between treatments ($p=0.0952$). Statistically significant differences were observed in the germination speed and the germination value ($p=0.0002$ and $p=0.0004$, respectively). The best results were recorded with the micro-sprinkler and subirrigation systems. The micro-sprinkler system had the highest peak value ($p=0.0151$), while the subirrigation system had the highest uniformity coefficient ($p=0.0494$) (Table 3). In cases with significant differences, manual irrigation had low values.

**Table 3.** Average values of germination parameters for *Pinus engelmannii* Carrière in different irrigation systems.

| Variable | Irrigation system | | | *p* value |
|---|---|---|---|---|
| | **Manual** | **Micro-sprinkler** | **Subirrigation** | |
| *GP* (%) | 81.4±0.22 c | 88.7±0.23 a | 85.3±0.17 b | <0.001 |
| *R₅₀* (days) | 10.2±0.02 a | 10.1±0.03 a | 9.8±0.02 a | 0.0952 |
| *GS* (days) | 7.2±0.12 b | 7.86±0.11 a | 7.72±0.09 a | 0.0002 |
| *GV* | 14.98±0.4 b | 17.52±0.5 a | 16.65±0.4 a | 0.0004 |
| *PV* | 5.87±0.09 b | 6.31±0.14 a | 6.23±0.1 ab | 0.0151 |
| *UC* | 0.19±0.01 b | 0.25±0.03 ab | 0.29±0.03 a | 0.0494 |

*GP* = Germination percentage; $R_{50}$ = 50 % of germination; *GS* = Germination speed; *GV* = Germination value; *PV* = Peak value; *UC* = Uniformity coefficient. Different letters in the same row indicate statistical differences between treatments ($p \leq 0.05$).

At the beginning of germination, imbibition is activated in the seed, and the availability of moisture plays a crucial role (Hernández-Anguiano et al. 2018). Hence, the importance of the efficiency of the irrigation system, as well as the growing medium, since the characteristics of the substrate used may or may not favor moisture content. In pine plant production, a base mix commonly used consists of peat, vermiculite, and perlite (2:1:1 v/v), components with high moisture retention (Aguilera-Rodríguez et al., 2023).

The lack of studies on irrigation and germination systems in *P. engelmannii* limits the comparison of results; however, the germination percentage obtained with the three irrigation systems was higher than that cited by Prieto-Ruíz and Rubio-Chaidez (1994), who, when studying the effect of seed planting depth in an interval of 0.5 to 2.0 cm in 100 % silt substrate, observed that at a shallower planting depth (0.5 cm) resulted in a higher germination percentage (66 %), and also recorded 50 % germination ($R_{50}$) at 16 days; that is, the delay was greater than in the present study (10 days). These

differences can be attributed to the fact that moisture in the micro-sprinkler system is concentrated at the top, as well as to the substrate used, since the base mixture provides physical properties that a silt substrate can hardly match.

For their part, Bustamante-García et al. (2012) obtained 98 % germination in *P. engelmannii* with seeds from seed stands. This result is higher than that of the present study, which is attributed to the loss of seed viability due to the time elapsed between harvesting (2016) and sowing (2024). There are other studies on the genus *Pinus* that analyze factors influencing germination, such as the one by Mendizábal-Hernández et al. (2015), who assessed the germination of *Pinus greggii* Engelm. *ex* Parl., and the one by Sánchez-Mendoza et al. (2023), who analyzed *Pinus hartwegii* Lindl. seeds but did not evaluate the irrigation factor; in their research, they considered that germination was affected by phenotypic characteristics and seed origin, while the present study highlights the crucial role of moisture in seed germination.

## Root development

The number of roots developed by plants across the different systems in the three sections of the container differed significantly ($p<0.0001$, $p=0.0035$, and $p=0.054$ for the upper, middle, and lower sections, respectively). The plants in the subirrigation and micro-sprinkler systems showed a larger number of roots in the upper and middle parts of the container; in the manually irrigated plants, a poor root system was observed, although it was more homogeneous in the three sections of the container. In terms of root length, there was no statistical difference in the lower section alone ($p=0.631$); the roots in the middle section were longer, with the subirrigation system standing out ($p=0.0433$). In the upper part, the roots were longer in the micro-sprinkler system ($p=0.0034$). In regard to the surface area and volume variables,

statistical differences were observed to occur only in the middle section of the container, and the subirrigation system proved superior in these variables ($p$=0.048, $p$=0.033, respectively; Figure 3).
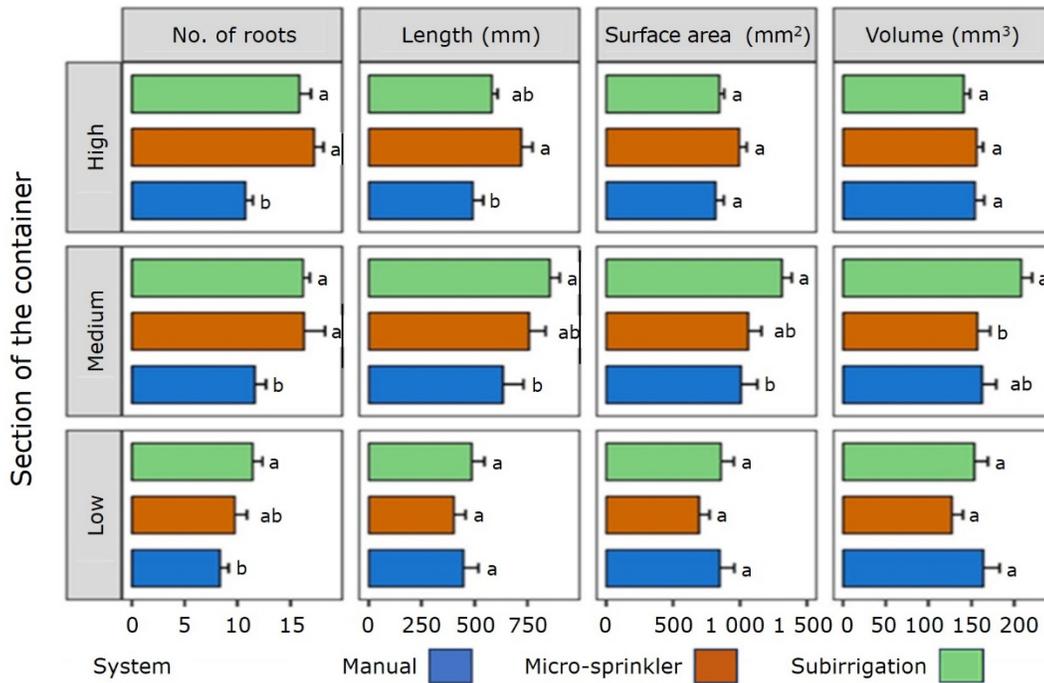


**Figure 3.** Characteristics of *Pinus engelmannii* Carrière roots by irrigation system.

The subirrigation system is not commonly used in forest nurseries in the country (Aldrete et al., 2023). This, despite the water use efficiency mentioned above, is because there is only one study that considers the production of *Pinus patula* Schiede *ex* Schltdl. & Cham. and *Pinus pseudostrobus* Lindl. by Ramírez-Galicia et al. (2022), who recorded savings of more than 50 % compared to manual irrigation, in addition to maintaining plant quality. However, they do not examine the radical development of the species in question.

For their part, Gallegos et al. (2020) point out that when plants are grown in containers, the root system tends to develop more at the bottom of the container and at the periphery, due to compaction from handling or to irrigation-induced compaction of the

substrate. In the present trial, the lower section did not show this effect, possibly because the evaluation was carried out almost one month after planting.

Pang et al. (2024) point out that the total root length and number of roots have a greater influence on plant anchoring in the field. In the present study, the highest number of roots was observed in plants watered with the micro-sprinkler and subirrigation systems in the upper and middle parts of the container. Therefore, it can be expected that these root systems will favor morphological development in later stages, since, as mentioned by Bar-Tal et al. (1997), the size of the root system is directly related to the efficiency of water and nutrient absorption, which affects root development. This, combined with mycorrhizal fungal colonization and its positive effects, allows the plant to adapt during the subsequent stages of the production process (Eissenstat et al., 2000; Salcido-Ruiz et al., 2020).

There are other adaptive characteristics of root systems that respond to different environmental factors and at the rhizosphere level, but water availability in particular clearly plays a key role in the evolution of the root system architecture (Sung et al., 2019). From a functional point of view, certain fine roots are primarily involved in the absorption of water and nutrients, while others participate in their transport and storage (Eissenstat et al., 2000).

# Conclusions

The subirrigation system consumes less water than the micro-sprinkler and manual systems. The type of irrigation system has a significant effect on the germination and root development stage of *P. engelmannii* in nurseries. Seedling emergence is greater with the micro-sprinkler system, while root development in the subirrigation system

shows greater length, surface area, and volume in the middle of the container than the other two systems. This research provides technical knowledge for a more efficient use of irrigation water during the production cycle of forest plants in nurseries.

## Acknowledgments

## Conflict of interest

The authors declare that they have no conflict of interest.

## Contributions by author

Enrique Santana-Aispuro: research conduction and management, data collection and analysis, interpretation of the results, and drafting of the manuscript; Jorge Armando Chávez-Simental: research management, research supervision, methodological design, verification of the results, interpretation of the results, and revision of the manuscript; José Ángel Sigala-Rodríguez: statistical analysis, interpretation of the

results, and revision of the manuscript; Arnulfo Aldrete: methodological design, interpretation of the results, revision of the manuscript; José Ángel Prieto-Ruíz: revision of the manuscript; José Rodolfo Goche-Télles: statistical analysis and revision of the manuscript.

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