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Research article

Aplicación de sustratos alternativos en la producción de *Pinus leiophylla* Schiede *ex* Schltdl. & Cham.

Alternative substrate application on the production of *Pinus leiophylla* Schiede *ex* Schltdl. & Cham.

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Abstract

The increment in forest plant production implies greater demands for fertilizers and commercial substrates. An alternative is organic amendments such as mixtures of biosolids and compost. The objective of this work was to determine the effect of both products as a substrate mixture for the production of *Pinus leiophylla* in a nursery. A randomized experiment with five replications was designed to test four mixtures composed of biosolids, compost and agricultural soil: M1: 70 % agricultural soil+30 % biosolids; M2: 70 % agricultural soil+30 % compost; M3: 50 % agricultural soil+30 % biosolids+20 % compost; M4: 50 % agricultural soil+20 % biosolids+30 % compost, and a Control with 100 % agricultural soil (five treatments). Morphological variables, quality indexes and foliar nutrient concentrations of the plants were determined to evaluate the response to the use of substrate mixtures. The statistical results showed that the addition of biosolids and mixed with compost favored plant development by presenting higher values in diameter, height and total dry weight (3.69 mm, 9.6 cm and 3.3 g) as well as relative growth in diameter (0.08 mm month^{-1}) and height (0.1 cm month^{-1}). M2 obtained the highest values of N, P and K compared to M4, which would imply greater absorption of these nutrients. The plant produced with these amendments developed quality attributes and increased foliar nutrient concentrations.

Keywords: Biosolids, compost, foliar nutrient concentration, forest specie, *Pinus* L., nursery.

Resumen

El incremento en la producción de planta forestal implica mayores demandas de fertilizantes y sustratos comerciales. Una alternativa son las enmiendas orgánicas como mezclas de biosólidos y composta. El objetivo de este trabajo fue determinar el efecto de ambos productos como mezcla de sustratos para la producción de *Pinus leiophylla* en vivero. Se diseñó un experimento al azar con cinco repeticiones para probar cuatro mezclas compuestas de biosólidos, composta y suelo agrícola: M1: 70 % suelo agrícola+30 % biosólidos; M2: 70 % suelo agrícola+30 % composta; M3:

50 % suelo agrícola+30 % biosólidos+20 % composta; M4: 50 % suelo agrícola+20 % biosólidos+30 % composta, y un Testigo con 100 % suelo agrícola (cinco tratamientos). Se determinaron variables morfológicas, índices de calidad y concentraciones nutrimentales foliares de las plantas para evaluar la respuesta del uso de mezclas de sustratos. Los resultados estadísticos mostraron que la adición de biosólidos mezclados con composta favorece el desarrollo de la planta, al presentar mayores valores en diámetro, altura y el peso seco total (3.69 mm, 9.6 cm y 3.3 g); así como crecimientos relativos en diámetro (0.08 mm mes^{-1}) y altura (0.1 cm mes^{-1}). La mezcla M2 obtuvo los mayores valores de N, P y K en comparación con la M4, lo que implicaría mayor absorción de estos nutrimentos. La planta producida con las enmiendas probadas desarrolló atributos de calidad y aumento en las concentraciones de nutrimentos foliares.

Palabras clave: Biosólidos, composta, concentración nutrimental foliar, especie forestal, *Pinus* L., vivero.

Introduction

In recent decades, the production of forest plants in nurseries has increased in Mexico, with the aim of carrying out reforestation and recovery actions in degraded areas (Comisión Nacional Forestal [Conafor], 2010) and the trend continues to rise. One of the essential materials for the production of plants in nurseries is the substrate, especially if rigid containers (tubes) are used. *Sphagnum* L. peat moss, known as "peat moss", has been one of the most used materials as a substrate in nurseries, due to the adaptability conferred by its physical and chemical characteristics (Pane et al., 2011). However, the use of these has caused environmental damage to peatlands due to the volumes of extraction, in addition to the fact that the demand for substrates has increased the cost; however, Caron and Rochefort (2013) indicate that the use of peat, for example, is not a problem, as they describe its use in the management of wetlands for its production (Vandiver et al., 2015).

The efficient use of resources involved in the production of forest species such as fertilizers has motivated the search for alternative substrates in nurseries, such as organic amendments from mixtures of biosolids and composts. Biosolids are by-products generated by wastewater treatment plants. Currently, these residues continue to accumulate because they have no defined subsequent use, which makes an alternative for reuse necessary, since most of them are deposited in the open air with a negative environmental impact.

As an option to its use, it has been proposed to use this material as a substrate (mixed with soil or other amendments) since it has physical and chemical characteristics suitable for the growth of plants in nurseries; however, Wang et al. (2021) identified that the nutrients and cations provided by biosolids can acidify the soil and modify the degree of mineral protection of the organic matter, which is not always convenient for the development of forest species.

There are antecedents of the use of biosolids as a substrate in the production of *Ceiba speciosa* (A. St.-Hil., A. Juss. & Cambess.) Ravenna, since when applied in high proportions, the height, diameter and biomass were higher compared to the coconut fiber mixture (Alonso et al., 2018). A similar result was recorded with *Pinus sylvestris* L. plants in which mixtures of biosolids with diatomite in a ratio of 75:25 and 50:50 (v/v) were favorable only for the diameter; while the substrate based on 100 % biosolids was superior in height, diameter, aboveground and root biomass (Kose et al., 2020). Mañas et al. (2010) reported that activated sludge showed better responses in the growth of *Pinus halepensis* Mill. seedlings, in the content of foliar nutrients and in the germination rate.

However, it is advisable to continue analyzing its feasibility of use, even though it has been discussed that the incorporation of biosolids, especially into forest soil, and high amounts of heavy metals can be toxic to microorganisms and reduce the absorption of essential nutrients in plants, but in the soil the concentration of potentially toxic elements for plants increases, although marginally (Bramryd, 2002, 2013).

As for the use of composts, positive effects have also been recorded in the forestry field, as described by Romero-Arenas et al. (2019) when using compost based on production residues of the *Lentinula edodes* (Berk.) Pegler fungus, in the production of quality *Pinus pseudostrobus* Lindl. plants. In addition to being a source of nutrition, favorable results have been observed from the use of compost tea, in the form of a biofertilizer, against pathological agents of the *Fusarium* Link genus (Otero et al., 2020). However, the quality of composts depends largely on the materials used for their preparation, from which arises the need to investigate different types of composts and their effect when mixed with other organic substrates, because their combination with biochar exceeds the diameter by 4 % compared to the use of compost alone in *Pinus banksiana* Lamb plants. (Slesak et al., 2022).

On the other hand, Simiele et al. (2022) described a contrary response, since the combined use of biochar and compost did not show any positive synergistic or cumulative effect and caused a reduction in the growth and development of potted *Popolus×euramericana* Guinier plants.

Pinus leiophylla Schiede *ex* Schltdl. & Cham., native to North America and naturally distributed in Mexico along the *Sierra Madre Oriental*, *Sierra Madre Occidental* and *Eje Neovolcánico*, is considered one of the most abundant conifers in the country's temperate forests (Flores et al., 2023; Ramírez-Orozco et al., 2022). It has significant ecological importance, especially in transition areas and agricultural frontier zones, where it can grow with restrictions on soil moisture and salinity, as well as resist fires due to its high post-fire regrowth capacity (Barton et al., 2023; Jimenez-Casas & Zwiazek, 2014).

In this context, the objective of this work was to determine the effect of biosolids and composts as substrate complements on the morphological characteristics and nutritional status of *Pinus leiophylla* produced in the nursery. The hypothesis that was raised was whether the use of biosolids and compost mixed with agricultural soil improves the morphology and leaf nutritional status of *P. leiophylla* plants in the nursery?

Materials and Methods

Location of the experiment

The experiment was carried out from October 2022 to September 2023 at the Experimental Forest Nursery of the Forest Sciences Division of the *Universidad Autónoma Chapingo* (*UACh*) (Autonomous University of *Chapingo*), with geographic coordinates 19°29’24” N and 98°52’15” W, at 2 283 masl. The *Pinus leiophylla* seeds used came from a natural stand located in *San Felipe*, *Tlaxcala*, Mexico (19°29’05” N and 98°35’40” W; altitude of 2 500 masl). They were sown on October 25; germination trays with perlite as a substrate were used as seedbeds. The transplant was made on November 9 to INNOVAPLAST® polypropylene tubes with a 305 cm^3 capacity. The experimental site was covered by a shade net with 70 % light transmissivity. The climate of the region is temperate with an average temperature of 16.4 °C and an average annual rainfall of 616.6 mm (Instituto Mexicano de Tecnología del Agua [IMTA], 2013).

Experimental and treatment design

A completely randomized experimental design was established with the following treatments:

Treatment 1. Control (T): 100 % agricultural soil.

Treatment 2. M1: 70 % agricultural soil+30 % biosolids.

Treatment 3. M2: 70 % agricultural soil+30 % organic compost.

Treatment 4. M3: 50 % agricultural soil+30 % biosolids+20 % compost.

Treatment 5. M4: 50 % agricultural soil+20 % biosolids+30 % compost.

Five replicates were defined per treatment and the experimental unit consisted of 25-cavity polypropylene forestry trays with a capacity of 305 cm^3 per cavity or tube.

Description of the substrates

Agricultural soil was the base substrate, since it is the main input used within the forest nursery itself. It was sifted with a 6×6 mm metal mesh and Vapam (AMVAC® Chemical Corporation, USA) was applied at a dose of 0.5 L in 20 L of water. It had a loamy texture, 7.64 pH, 0.6 dS m^{-1} electrical conductivity and 1.03 % organic matter; concentration of 0.2 % N, 4.2 mg kg^{-1} P and 4.02 cmol kg^{-1}. The biosolids were obtained from the *Atotonilco* Wastewater Treatment Plant (WWTP) in *Atotonilco de Tula*, in the state of *Hidalgo*. They comply with the parameters and maximum permissible limits established by the Mexican Official Standard NOM-004-SEMARNAT-2002 (NOM-004-SEMARNAT-2002, 2002), which allows their use for forest and soil improvement. They had a 8.65 pH; 2.3 dS m^{-1} electrical conductivity, 46.3 % organic matter, 68.7 % moisture and a concentration of 4.12 % N, 2.06 % P and 0.26 % K.

On the other hand, the compost was obtained from sheep and cattle manure and domestic waste. It presented a pH of 9.1, electrical conductivity of 6.8 dS m^{-1}, 33.3

% organic matter and 36.2 % moisture. The nutritional contribution was 1.38 %, 0.74 % and 2.37 % of N, P and K respectively.

Variables to be evaluated

At 10 months of age of the plants, the diameter at the root neck (*D*, mm) was determined with a model Her-411 Steren® digital vernier caliper; the total height (*H*, cm) with a model MGA 5020 Cadena® flexometer, graduated in cm and mm. The plants were separated into root, stem and foliage and placed in a model 1600 Hafo-Series Shel Lab® electric oven at 70 °C for 48 hours to determine the dry weights (g) with a model PRO32F Sartorius® digital scale with one centigram of precision; the root dry weight (*RW*, g), the aerial dry weight (*AW*, g) and the total dry weight (*TW*, g) were obtained. With these variables, the Relative Growth Rate in Diameter (*RGD*, mm $month^{-1}$) and in Height (*RGH*, cm $month^{-1}$) were calculated with Equation 1 (Pallardy, 2008):

$$RG = \frac{ln(X_2) - ln(X_1)}{\Delta t} \qquad (1)$$

Where:

RG = Relative growth

ln = Natural logarithm

X_1 = Variable measured on the first date

X_2 = Variable measured on the last date

Δt = Time between both measurements

The first measurement date was in January 2023 and the last measurement in September 2023. Plant quality indicators were also determined, such as the shoot-to-root ratio (*PAR*), dividing the *AW* and the *RW*; indices such as the Slenderness Index (*SI*) dividing the *H* by the *D* (Johnson & Cline, 1991) and the Dickson Quality Index (*DQI*), Equation 2 (Dickson, 1960):

$$DQI = \frac{TW(g)}{\frac{Height\ (cm)}{Diameter\ (mm)} + \frac{AW\ (g)}{RW\ (g)}} \qquad (2)$$

Where:

TW = Total dry weight

AW = Aerial dry weight

RW = Root dry weight

Nutritional analysis

Foliar concentrations of N, P, K, Ca, Mg, Mn, B, Cu, Fe and Zn were determined. Composite samples of foliage from five plants were prepared with four replicates per treatment. N was determined by the Semimicro-Kjeldahl method (Bremner, 1965); the rest of the elements were made from the extract resulting from the digestion of HNO_3:HCl_4 (2:1, v:v) of dried and ground plant tissue, with a model Series ICP-OES 725 Agilent® atomic emission spectrophotometer.

Data analysis

The effect of treatments on morphological, quality and nutritional variables were analyzed using an Analysis of Variance (ANOVA) in the R software (R Core Team, 2022), with a reliability of 95 % ($p<0.05$). To identify differences between the mixtures, a comparison of means was made with the Tukey test ($\alpha=0.05$). The diagnosis of the nutritional status was carried out using the vector graphic method (Timmer & Stone, 1978) and with the interpretation of the nomograms (López-López & Alvarado-López, 2010); the nutritional status of the Control treatment was taken as a reference point. The statistical model used was the following (Equation 3):

$$Y_i = \mu + \alpha_i + e_i \qquad (3)$$

Where:

Y_i = Response variable

μ = General mean of the data

α_i = Difference of the mean of the i-th treatment

e_i = Experimental error

Results and Discussion

Morphological variables and quality indexes

The ANOVA indicated highly significant differences in all study variables (p=0.0001); in particular, the M1 mixture (70 % agricultural soil+30 % biosolids) showed the highest values of all morphological variables and quality indexes, except for root dry weight and Slenderness index (Table 1).

Table 1. Mean and standard deviation of morphological variables and quality indexes of *Pinus leiophylla* Schiede *ex* Schltdl. & Cham. plants at nursery stage produced in different substrate mixtures.

Variable	Treatment				
	Control	M1	M2	M3	M4
D (mm)	3.81±1.00d	7.50±2.90a	2.51±0.60e	6.29±2.50b	5.03±2.00c
H (cm)	9.23±3.00c	18.83±90a	7.45±4.30d	18.53±12.80a	14.51±5.90b
RW (g)	0.75±0.10d	1.32±0.20b	0.38±0.10e	1.54±0.30a	0.99±0.10c
AW (g)	0.72±0.10c	3.45±1.00a	0.51±0.10c	3.2±1.10a	1.95±0.40b
TW (g)	1.47±0.30c	4.77±1.80a	0.89±0.20d	4.75±2.20a	2.94±1.00b
RGD (mm month^{-1})	0.20±0.01d	0.28±0.02a	0.16±0.02e	0.25±0.01b	0.23±0.02c
RGH (cm month^{-1})	0.13±0.01c	0.23±0.01a	0.12±0.01c	0.21±0.01a	0.19±0.01b
PAR	0.98±0.04d	2.47±0.6a	1.45±0.30c	2.19±0.30b	2.04±0.10b
SI	2.54±0.40b	2.68±0.90ab	3.1±0.60a	3.08±0.60a	3.06±0.70a
DQI	0.44±0.05c	0.94±0.10a	0.21±0.02d	0.96±0.20a	0.62±0.1b

Control = 100 % agricultural soil; M1 = 70 % agricultural soil+30 % biosolids; M2 = 70 % agricultural soil+30 % organic compost; M3 = 50 % agricultural soil+30 % biosolids+20 % compost; M4 = 50 % agricultural soil+20 % biosolids+30 % compost. *D* = Diameter (mm); *H* = Height (cm); *RW* = Root dry weight; *AW* = Aerial dry weight; *TW* = Total dry weight; *RGD* = Relative diameter growth; *RGH* = Relative height growth; *SI* = Slenderness Index; *DQI* = Dickson Quality Index. Different letters within a column indicate differences (p<0.05) with Tukey.

The M1 exceeded the Control treatment by 3.69 mm, 9.6 cm, and 3.3 g in diameter, height, and total dry weight, respectively. In addition, it recorded higher relative growth values in diameter (0.08 mm month^{-1}) and height (0.1 cm month^{-1}). The previous results regarding the aerial dry weight values may indicate a better health condition of the plants, since they have more foliage, which is associated with the physiological processes and roots of the plants (Moreno et al., 2021).

Regarding the M2 substrate (70 % agricultural soil+30 % organic compost), low values were obtained in all variables, except for the Slenderness Index, which recorded values below the Control (1.3 mm in diameter and 1.78 cm in height). The *TW* value was 0.89 g, (0.58 g less than the Control) and 3.88 g less than the M1 mixture.

The morphological results suggest that the incorporation of biosolids (30 %) as part of the substrate was favorable for the production of *Pinus leiophylla* plants. The M1 and M3 mixtures, which include the 30 % portion of biosolids, exceeded 4 mm in diameter and 15.25 cm in height, and in accordance with the quality parameters recommended by the National Forest Commission to guarantee greater plant survival in the field (Conafor, 2010). On the other hand, according to the Mexican Standard NMX-AA-170-SCFI-2016, a diameter ≥4 mm is acceptable as an indicator of plant quality in the nursery for *Pinus leiophylla* (NMX-AA-170-SCFI-2016, 2016). These data compared with the Control reflect that the use of nutritional sources in the nursery directly favors the morphology of the plant (Grossnickle & MacDonald, 2018; Heras-Marcial et al., 2023). They also agree with what was observed by Melo et al. (2019), who report that biosolids combined with substrates such as the bark of *Bactris gasipaes* Kunth (1:2, 1:3 v:v) promote higher values in height, diameter and dry matter in 120-day-old *Schinus terebinthifolius* Raddi plants.

The average diameter of all treatments was 5.03 mm, a higher figure compared to other one-year-old *Pinus leiophylla* individuals (3.5 mm) produced under a technified system with controlled-release fertilizers (Palacios et al., 2015). The average height was 13.7 cm and the Dickson Quality Index of 0.634, exceeding that described by Buendia et al. (2020) when applying exponential fertilization to six-month-old *Pinus* *leiophylla* specimens in the nursery. Similarly, in another experiment with four-month-old trees of the same species and constant and exponential fertilization treatments, the values of diameter, height, *DQI* and total dry weight were lower (Buendia et al., 2016) with a lower average height (13.71 cm) compared to seven-month-old individuals produced in a polyethylene bag system (28.4 cm) (Pineda et al., 2020).

Regarding the *DQI*, the mixtures M1, M3 and M4 showed values higher than 0.5, indicating high quality of the produced plant according to the classification of Rueda-Sánchez et al. (2014) and Sáenz et al. (2018). The Slenderness Index (*SI*) is an indicator of the plant's resistance to wind desiccation, survival and potential growth in dry sites and its value must be less than 6. In this case, all treatments were below the value of 6 (Rueda-Sánchez et al., 2014). The aerial part-root ratio (*PAR*), according to Rueda-Sánchez et al. (2014), the plant produced in the mixtures M1, M3 and M4 are classified as medium quality plants. The indicator relates the aerial part to the root part, according to the author if the aboveground biomass is greater than that of the root, and is associated with low rainfall where root development is not sufficient to supply the aerial part of the plant (Thompson, 1985).

Foliar nutrient concentration

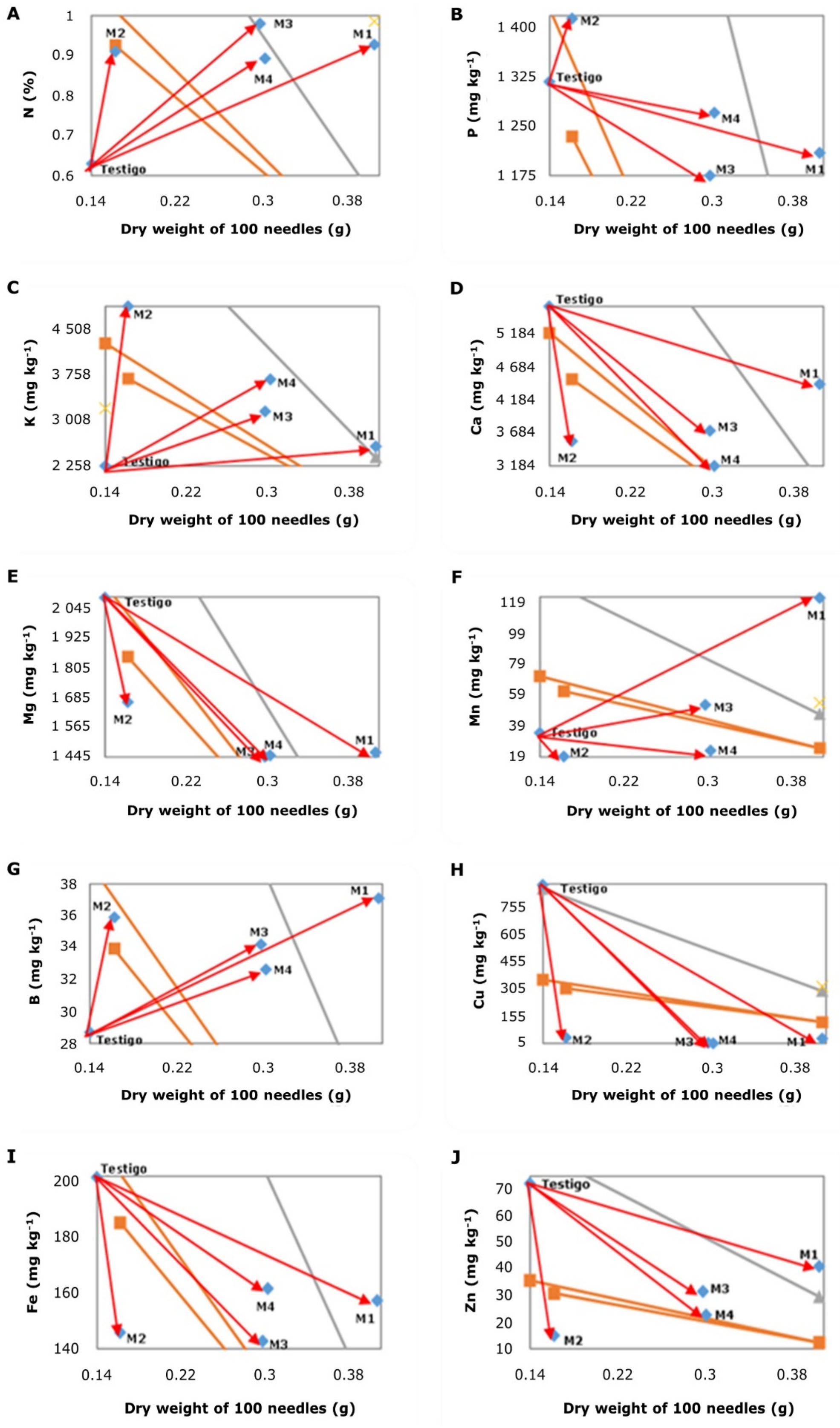
Treatment M1 recorded the highest foliar concentrations of Mn and B. Treatment M3 (50 % agricultural soil+30 % biosolids+20 % compost), exceeds by 0.35 % of N the Control that had the lowest value. Treatment M2 (70 % agricultural soil+30 % organic compost) recorded the highest levels of P and K, above the Control by 96.9 mg kg^{-1} and 2 638.8 mg kg^{-1} respectively. The Control exhibited the highest foliar concentrations of Ca, Mg, Cu and Zn, while no significant differences were found for Fe (Table 2).

Table 2. Means and standard deviation of foliar nutrient concentrations of *Pinus leiophylla* Schiede *ex* Schltdl. & Cham. plants produced in the nursery in different substrate mixtures.

Variable	Treatment				
	Control	**M1**	**M2**	**M3**	**M4**
N (%)	0.63 ±0.10b	0.93 ±0.20ab	0.91 ±0.10ab	0.98 ±0.10a	0.89 ±0.20ab
P (mg kg^{-1})	1 318.50 ±127.40ab	1 210.10 ±134.60ab	1 415.40 ±65.10a	1 175.10 ±82.60b	1 271.50 ±59.70ab
K (mg kg^{-1})	2 258.60 ±157.00b	2 583.10 ±185.00cd	4 897.40 ±144.00a	3 159.50 ±216.00bc	3 692.20 ±412.00b
Ca (mg kg^{-1})	5 619.40 ±547.70a	4 432.10 ±218.30b	3 561.80 ±293.80c	3 721.20 ±347.1bc	3 184.20 ±246.00c
Mg (mg kg^{-1})	2 092.10 ±26.90a	1 463.40 ±114.70b	1 667.60 ±166.60b	1 445.90 ±77.50b	1 450.90 ±83.50b
Mn (mg kg^{-1})	34.60 ±3.20b	122.40 ±29.00a	19.30 ±0.80b	52.80 ±13.00b	23.07 ±2.00b
B (mg kg^{-1})	28.71 ±1.90b	37.10 ±4.90a	35.90 ±2.10ab	34.21 ±3.00ab	32.64 ±2.60ab
Cu (mg kg^{-1})	880.00 ±585.00a	32.48 ±26.40b	38.09 ±32.50b	9.79 ±2.50b	7.02 ±0.50b
Fe (mg kg^{-1})	201.50 ±62.00a	157.37 ±18.60a	145.80 ±23.90a	142.70 ±26.20a	161.60 ±22.30a
Zn (mg kg^{-1})	72.20a	41.01ab	15.00b	31.59b	22.69b

Control = 100 % agricultural soil; M1 = 70 % agricultural soil+30 % biosolids; M2 = 70 % agricultural soil+30 % organic compost; M3 = 50 % agricultural soil+30 % biosolids+20 % compost; M4 = 50 % agricultural soil+20 % biosolids+30 % compost. Different letters within a column indicate differences (p<0.05) with Tukey.

The trends behave in a similar way in the N concentrations (Figure 1A), K (Figure 1C) and B (Figure 1G). On the other hand, the graphs of Ca (Figure 1D), Mg (Figure 1E), Cu (Figure 1H), Fe (Figure 1I) and Zn (Figure 1J) reflect another group of trends, which was common to all the mixtures since they reflected an increase in the dry weight of the needles. P (Figure 1B) except for M2, shows the same trend as the second group. This is also observed in Mn (Figure 1F) where, except for M2, the trend is similar to the first group.


A
N (%)
1
0.9
0.8
0.7
0.6
M2
M3
M1
M4
Testigo
0.14
0.22
0.3
0.38
Dry weight of 100 needles (g)
B
P (mg kg-1)
1 400
1 325
1 250
1 175
M2
Testigo
M4
M3
M1
Dry weight of 100 needles (g)
C
K (mg kg-1)
4 508
3 758
3 008
2 258
M2
M4
M3
M1
Testigo
Dry weight of 100 needles (g)
D
Ca (mg kg-1)
5 184
4 684
4 184
3 684
3 184
Testigo
M1
M3
M2
M4
Dry weight of 100 needles (g)
E
Mg (mg kg-1)
2 045
1 925
1 805
1 685
1 565
1 445
Testigo
M2
M3
M4
M1
Dry weight of 100 needles (g)
F
Mn (mg kg-1)
119
99
79
59
39
19
M1
M3
Testigo
M2
M4
Dry weight of 100 needles (g)
G
B (mg kg-1)
38
36
34
32
30
28
M1
M2
M3
M4
Testigo
Dry weight of 100 needles (g)
H
Cu (mg kg-1)
755
605
455
305
155
5
Testigo
M2
M3
M4
M1
Dry weight of 100 needles (g)
I
Fe (mg kg-1)
200
180
160
140
Testigo
M4
M1
M2
M3
Dry weight of 100 needles (g)
J
Zn (mg kg-1)
70
60
50
40
30
20
10
Testigo
M1
M3
M4
M2
Dry weight of 100 needles (g)

Testigo = Control. Control = 100 % agricultural soil; M1 = 70 % agricultural soil+30 % biosolids; M2 = 70 % agricultural soil+30 % organic compost; M3 = 50 % agricultural soil+30 % biosolids+20 % compost; M4 = 50 % agricultural soil+20 % biosolids+30 % compost.

Figure 1. Timmer nomograms of foliar nutrient concentrations of *Pinus leiophylla* Schiede *ex* Schltdl. & Cham. grown in the nursery in different substrate mixtures.

The Control treatment was deficient in N, K and B, and these deficiencies were remedied by treatments with biosolids (M1), compost (M2) and their combinations (M3 and M4), which explains the positive responses in the dry weight of needles (Figure 1). The promotion of growth by biosolids and composts, alone applied to the soil or combined with compost, generated the dilution of P, Ca, Mg, Cu, Fe and Zn in the foliage of the plants, indicating that neither the biosolids nor the compost were sufficient to cover the requirements of these nutrients by the plants (López-López & Alvarado-López, 2010). The results obtained are comparable to those obtained by Buendía et al. (2016) where the average of N (0.87 %), P (1 278 mg kg^{-1}) and K (3 318 mg kg^{-1}) of all treatments was below the average of N (2.65 %), P (2 303 mg kg^{-1}) and K (4 235 mg kg^{-1}) with chemical fertilization, maintaining the nutritional relationship of the elements, where N is lower by 1.6 %, 879 mg kg^{-1} in P and 773.34 mg kg^{-1} of K.

Compared with other forest species, foliar concentrations of P and K are lower than those reported for 10-month-old *Pinus greggii* Engelm. *ex* Parl. seedlings in a nursery, but not those of N (Vicente-Arbona et al., 2019). Martínez-Nevárez et al. (2023) obtained in a controlled fertilization trial in one-year-old *Pinus cooperi* C. E. Blanco, higher values in N by 0.4 %, compared to the Control treatment and by 0.4 % in the M3 mixture; but a lower average value in P (787 mg kg^{-1}). Aguilera-Rodríguez et al. (2021) in a test with *Pins patula* Schltdl. & Cham. seven-month-old plants with different types of sawdust and chemical fertilizers, reported higher values for N (1.39

%), P (2 055 mg kg^{-1}), K (48 855 mg kg^{-1}) and Mn (287 mg kg^{-1}); while the nutrients Ca (2 264 mg kg^{-1}), Mg (791 mg kg^{-1}), B (19 mg kg^{-1}), Cu (11 mg kg^{-1}), Fe (68 mg kg^{-1}) and Zn (27 mg kg^{-1}) were higher in this study. This may be a reflection of the substrate and source of nutrition itself, in this case biosolids, in addition to the difference between species. This may be an indication that it is important to know the appropriate proportion of biosolids in order not to increase the concentration of nutrients such as Cu and Zn in plants. However, in general, the addition of biosolids alone with the soil and mixed with compost, reflected an increase in the morphological characteristics of the seedlings, coinciding with what was observed in other species such as *Pinus cembroides* Zucc. (Madrid-Aispuro et al., 2020) after 14 months in the nursery. The viability of using compost in the nursery as an alternative substrate has been shown in species such as *Juniperus polycarpos* K. Koch (Negi et al., 2022) and *Castanea sativa* Mill. (Fuertes-Mendizábal et al., 2021), with lower proportions than those applied in this study.

Conclusions

The morphological characteristics of *Pinus leiophylla* plants produced in substrates based on biosolids and composts develop better diameter, height and biomass, compared to those produced in agricultural soil (Control). The plant quality indexes and the nutrient concentrations in foliage show that the use of biosolids for the production of forest plants is a good alternative, with beneficial impacts in terms of saving chemical fertilizers. The tested treatments were applied even when the biosolids presented pH intervals above the recommendation; however, balanced proportions with soil and compost are agronomically viable in the production of the *Pinus* genus. In perspective, the application of biosolids in non-edible species such as cotton, cut flowers and other forest species is recognized, so it is suggested to continue with the analysis on the viability of using biosolids as a complement to soil.

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Conflict of interest

The authors declare that they have no conflict of interest.

Contribution by author

Pedro Sinai Rivera Torres: study planning, writing of the manuscript, data collection, analysis and interpretation of results; Jorge Flores Velázquez: study direction, writing of the manuscript; Miguel Ángel López López: study planning, analysis and interpretation of results, writing of the manuscript; Erickson Basave Villalobos, Abdul Khalil Gardezi and Carlos Ramírez Ayala: advice and writing of the manuscript.

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