Different nursery techniques in the production of *Quercus crassifolia*

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Abstract

Mexico is the country with the highest number of species of the genus *Quercus*, but there has been little research on their propagation in nurseries. *Quercus crassifolia* is distributed across more than 50% of the national territory; however, no studies have been conducted to document its morphological growth and plant quality in nurseries for reforestation and forest restoration. Some of the key factors in plant production, principally in a technified system, are the selection of containers, substrates, and fertilizer doses. This study therefore evaluated two container sizes, two mixtures of organic substrates, and two doses of controlled-release fertilizer. After nine months of growth in the nursery, morphometric parameters of the plants were recorded, and quality indices were determined based on these values. The results showed that container size, substrate choice, and fertilization dose all influenced the quality of the plant produced. With both fertilizer doses, the 25:25:50 substrate mixture of fresh pine sawdust, composted pine bark, and moss peat produced plants with the highest values of height, diameter, and shoot, root, and total dry biomass. Considering the factors evaluated, the use of 200 mL containers with the aforementioned substrate mixture and the addition of 7 g L^{-1} of controlled-release fertilizer will produce plants of *Quercus crassifolia* suitable quality for use in reforestation.

Keywords

Containers; Fertilization; Oak; Substrates

Contents

1 Introduction

It is estimated that there are around 435 species of oak worldwide (Hipp et al. 2017; Kremer and Hipp 2020), of which 170 are found in Mexico and 109 are endemic to the country (Rodríguez-Trejo and García-Pascual 2021). The genus *Quercus* is ecologically significant due to its wide geographical and elevational distribution, as well as its abundance in the temperate and subhumid mountainous regions of Mexico (Hernández-Ramos et al. 2022).

Oak trees contribute to biomass production, oxygen generation, and atmospheric regulation, among other benefits (González-Elizondo et al. 2012). Its wood ranks second in terms of use (1,210,740 m^{-3} per year) in Mexico, forming the economic basis of rural communities as a source of energy for domestic consumption (firewood and charcoal) and industrial use in the production of lumber, cellulosics, veneers, plywood, posts, construction structures, furniture, handicrafts, and tool handles (SEMARNAT, 2021). However, the oak forests present declining populations and productivity due mainly to agricultural and livestock production practices, as well as the incidence of forest fires (Rosaliano-Evaristo et al. 2024). Moreover, there is a lack of action to counteract the adverse impacts, no species of the genus *Quercus* is included in the legal framework of protection of species in Mexico (NOM-059-SEMARNAT-2010), and the programs of restoration do not consider them as priority for reforestation (Hernández and Badano 2017). This is due in large part to the limited knowledge regarding the ecology and distribution of these species.

In Mexico, oak trees are not usually included in reforestation and restoration programs, even though the vegetation, specifically in the forest ecosystems they inhabit, consists of species of the genus *Quercus* or associations with pine species (González-Elizondo et al. 2012). Mass production of oak species in forest nurseries for reforestation and ecological restoration is therefore necessary. However, studies on their propagation in nurseries have focused mainly on four species: *Q. canbyi* Trel., *Q. rugosa* Née, *Q. crassipes* Bonpl., and *Q. durifolia* Seemen (Villalón-Mendoza et al. 2016; De Jesús et al. 2021; Venancio et al. 2022; Madrid-Aispuro et al. 2025). Another species of great importance for silviculture is *Quercus crassifolia* Humb. & Bonpl., which has a wide distribution in Mexico, being found in more than 50 % of the national territory (Gorgonio-Ramírez et al. 2017). This species has high potential for industrial use, thanks to the qualities of its wood, which responds favorably to processes such as turning, drilling, molding, and sanding (Flores-Velázquez et al. 2013). It is also notable for its utility in degraded soil restoration programs (Rubio-Licona et al. 2011). Given the above, there is a need to develop studies on the production of *Q. crassifolia* plants in nurseries to supply reforestation programs for ecological restoration purposes.

Reforestation is the main tool for forest restoration, and its success depends on the quality of the plants produced in the forestry nurseries (Duque-Lazo et al. 2018). The particular cultural practices (for example, irrigation, fertilization, pruning, management of temperature and light using shade mesh, and integrated management of pests and diseases) employed have a significant impact on the morphological and physiological quality of the plant material, since this factor can increase its probability of growth and survival in adverse environmental conditions in the field (Grossnickle and MacDonald 2018). The factors that affect plant growth in nurseries include container, substrate, and fertilization (Madrid-Aispuro et al. 2020; Gabira et al. 2021). In this regard, the size and shape of the container are related to the distribution of the shoot and root biomass of the plants and, therefore, can influence survival and growth in the field (Aldrete et al. 2023a; Mariotti et al. 2015a). For instance, container depth can determine the growth of the root system and length of the taproot, which in turn can affect the plant's ability to explore deeper soil layers (Chirino et al. 2008). Likewise, modern containers are designed with rigid walls and several internal vertical grooves that direct root growth downward, preventing lateral roots from curling and promoting a more fibrous and balanced root architecture in the plants (Benítez-Favela et al. 2025). The design of the container used in the production of plants has a direct influence on the structure of their roots given the plasticity of the root system during their development (Grossnickle and Ivetić 2022).

The substrates or growth media used in forestry nurseries for container plant production are materials that, alone or in mixtures, ensure better growth conditions for the plants (Gruda 2009). For this, they must present certain essential characteristics to be used as a substrate, including being lightweight, friable, capable of retaining water and air, and easily drained, with a pH between 5.8 and 6.5, and an electrical conductivity of less than 1 dS m^{-1}. They must also be free of toxic substances, pests, pathogenic microorganisms, and nematodes (Fussy and Papenbrock 2022).

Peat is the substrate most commonly used in technified forestry nurseries for plant production due to its suitable physical, chemical, and biological properties (Fussy and Papenbrock 2022), mainly because it has a considerable water retention capacity, which makes it an ideal medium for plant growth worldwide (Hussain et al. 2014). However, its availability is limited in some regions, its importation is costly, and its extraction has significant ecological impacts given that peatlands are an important reservoir of carbon, but they take a long time to regenerate (Atzori et al. 2021; Heiskanen et al. 2024). Given the environmental challenges associated with the intensive use of peat, it is imperative to identify sustainable alternatives.

In this context, sawdust and composted bark, by-products generated by the sawmill industry, have potential as substrates in the production of forest plants in nurseries. Moreover, they are widely available given the large quantities of each produced in Mexico (Mateo et al. 2023). According to Pineda et al. (2019), the use of fresh sawdust has a suppressive effect on the development of pathogenic microorganisms such as *Fusarium*, *Rhizoctonia*, *Streptomyces*, and *Phytium*, which attack the roots of plants in the nursery stage. Incorporation of these materials could enable the generation of low-cost products that have a long-term positive ecological impact (Pineda-Pineda et al. 2012).

Fertilization promotes plant survival through a variety of mechanisms, including strengthening the root system for water extraction from the soil, promoting biomass production, improving photosynthetic efficiency, and creating conditions for greater resistance to hydric stress and adverse environments (Zia et al. 2021). In recent years, the use of controlled-release fertilizers (CRF) as a source of nutrition in forestry plant production in nurseries has had a significant positive impact (Aguilera-Rodríguez et al. 2016; González-Orozco et al. 2018; Madrid-Aispuro et al. 2020).

The CRF are designed to release nutrients gradually, ensuring that their release is tailored to the specific needs of the plant (Moradi et al. 2024). Previous studies suggest that their application improves plant quality, reduces nitrate (NO_3) leaching, decreases ammonia (NH_3) volatilization, and reduces nitrous oxide (N_2O) emissions, which contribute to greenhouse gas levels in the atmosphere (Wei et al. 2020; Madrid-Aispuro et al. 2020; González-Alemán et al. 2025). In addition, CRF save on inputs, labor, and time since they are applied only once. To determine appropriate fertilizer doses, the species, substrate, and fertilizer type must be considered to achieve the highest efficiency in nutrient use (Agro and Zheng 2014).

The objective of this study was therefore to evaluate the impact of two container sizes, two mixtures of organic substrates, and two doses of controlled-release fertilizer on the morphological characteristics of *Quercus crassifolia* following nine months of growth in a nursery. The study hypothesizes that the larger container with at least one substrate mixture and the high fertilizer dose will result in greater values of morphological growth parameters of the plants.

2 Materials and methods

2.1 Study area

The experiment was conducted at the forestry nursery of the Facultad de Ciencias Forestales y Ambientales of the Universidad Juárez del Estado de Durango (FCFA-UJED) in Mexico, located at Río Papaloapan and Blvd. Durango (24° 00’ 48.3” N and 104° 41’ 10.36” W, at an elevation of 1,870 masl). The growth cycle lasted nine months, from January 5 to April 5, 2024. The plant grew in a greenhouse covered with polythene of caliber 720 µm that had been treated against ultraviolet rays. From April 6 to October 10 of the same year, the plant were kept in an area under metal structures and with a 60% shade. The temperature in the plant growth area was recorded with a data logger model RC-4HC (Figure 1).

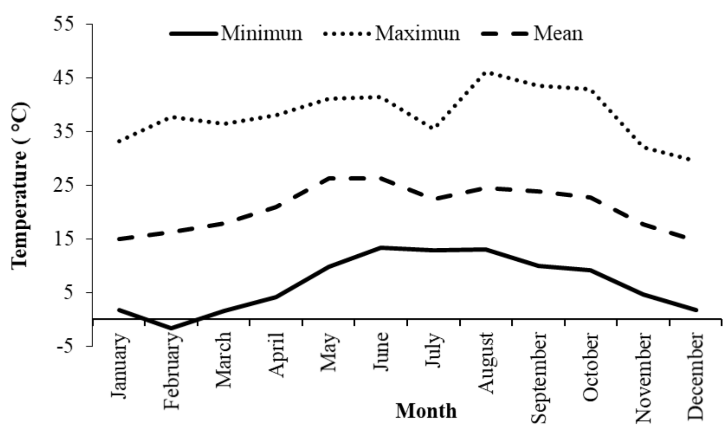

Figure 1. Monthly record of minimum, maximum, and mean values in *Quercus crassifolia* growth in a nursery.

2.2 Production of plants and treatments

Acorns were collected on November 25, 2023, from the crowns of four trees in a natural stand dominated by pines and oaks in Otinapa, in the municipality of Durango, Mexico (24°03'27" N and 105°00'54" W, at an elevation of 2,397 masl). The acorns were stored for six weeks at 4 °C in a refrigerator. As a pre-germination treatment, the acorns were soaked in water at ambient temperature for 12 hours before sowing. Subsequently, two acorns were sown in each cells of the container with the substrate mixture and the corresponding fertilizer dose, according to treatment, at a depth of 2 cm. Germination occurred an average of 18 days after sowing at a rate of 97 %. Where both acorns germinated in a single cavity, one plant was removed. The plants were watered lightly every day during the germination stage. Once germination had occurred, watering was reduced to once every three days.

Eight treatments were evaluated, derived from two types of containers, two substrates, and two fertilization doses (Table 1). The containers evaluated were expanded polystyrene with 77 cavities of 170 mL^{-1} per cavity, 15 cm in length and 43 mm in upper diameter (CPOL-170), and black polypropylene plastic with 54 cavities of 200 mL^{-1} per cavity, 14.4 cm in length and 50 mm in upper diameter (CPLA-200). The plastic containers were washed and disinfected in water with 10 % sodium hypochlorite, while the polystyrene containers were immersed in a preparation of 100 L of water, 1 L of copper sulfate ($CuSO_4$), and 1 L of sealant to promote chemical root pruning.

The substrate mixtures evaluated comprised fresh pine sawdust (PS), composted pine bark (CB), and moss peat (MP) at different proportions: 1) 50:20:30 of PS-CB-MP, and 2) 25:25:50 of PS-CB-MP (Table 1).

Two doses (7 and 10 g L^{-1}) of Multicote 8® 18-6-12+2Mg+M.E. controlled-release fertilizer (Haifa Chemicals Ltd.-Haifa, Israel) were applied, with an eight-month release period. The fertilizer was incorporated into the substrate during its preparation before sowing the acorns (Table 1).

Table 1. Containers, substrates, and fertilizer doses evaluated in the production of *Quercus crassifolia* over nine months in a nursery.

Treatment	Container	Substrate (%) PS-CB-MP	Fertilizer dose (Multicote 8® 18-6-12 of NPK)
T1	Polystyrene 170 mL	50-20-30	7 g L^{-1}
T2	Polystyrene 170 mL	50-20-30	10 g L^{-1}
T3	Polystyrene 170 mL	25-25-50	7 g L^{-1}
T4	Polystyrene 170 mL	25-25-50	10 g L^{-1}
T5	Plastic 200 mL	50-20-30	7 g L^{-1}
T6	Plastic 200 mL	50-20-30	10 g L^{-1}
T7	Plastic 200 mL	25-25-50	7 g L^{-1}
T8	Plastic 200 mL	25-25-50	10 g L^{-1}

Where: PS=pine sawdust, CB=composted bark, MP=moss peat

2.3 Experimental design

The treatments were distributed in a completely randomized experimental design with a 2 x 2 x 2 factorial arrangement (two container types, two substrate mixtures, and two fertilizer doses), generating eight treatments. Each treatment consisted of four replicates, considering 35 plants in the polystyrene containers and 24 plants in the plastic containers, per experimental unit.

2.4 Morphological evaluation

When the plants were nine months old (Figures 2 and 3), 10 specimens were randomly selected per replicate, 40 per treatment (320 plants in total), and the following measurements were taken: height (cm), root collar diameter (mm), shoot, root, and total dry biomass (g), the main root biomass (g), and secondary roots (g). In the case of biomass, the plants were divided into two parts: the shoot part (stems and leaves) and the root part (the set of roots). Both parts were placed separately in kraft paper bags and dried at 70 °C for 72 h in a drying oven (Ecoshel® model 9024A). They were then weighed on an analytical balance (Ohaus® model Pioneer PA512) to determine the dry mass per component. The dry weight values were used to calculate the Dickson quality index, the shoot/root ratio, and the allocation of biomass to the leaves, stems, and roots. The robustness index was also calculated by dividing the height (cm) by the root collar diameter (mm) of the plants.

Figure 2. Morphological aspect of a plant produced in a plastic container of volume 200 mL, at nine months after sowing.

Figure 3. Morphological aspect of a plant produced in an expanded polystyrene container of volume 170 mL, at nine months after sowing.

2.5 Statistical analysis

The residuals of the evaluated variables were analyzed using the Shapiro-Wilk and Levene tests to verify the assumptions of normal distribution and homogeneity of variances, respectively. Once the assumptions were determined, analyses of variance were performed to detect statistical differences in the response variables. In cases where statistical differences were found, Tukey's mean separation tests were performed to obtain the statistical groups. The value of statistical significance used in the analyses was $p<0.05$. All analyses were performed with the statistical software version 4.4.1. (R Core Team 2024).

3 Results and discussion

The analysis of variance showed significant differences (p <0.05) in the factor substrate mixture for most of the variables evaluated, except for the main root biomass and Dickson quality index. Container size influenced the variables height, dry root biomass, secondary roots, and robustness index. Fertilizer dose favored the growth of root dry biomass, total dry biomass, main root, secondary roots, Dickson quality index, and the shoot/root ratio. Finally, the interaction among factors showed a significant effect on all variables evaluated (Table 2).

The *Q. crassifolia* plants produced in the containers CPLA-200 mL presented greater height and root dry biomass compared to those produced in the containers CPOL-170 mL. However, no significant differences were observed between the two container types in terms of the diameter, shoot dry biomass, and total biomass. Regarding the factor substrate, the plants produced in the mixture 25:25:50 PS-CB-MP presented greater values of height, diameter, and shoot, root, and total dry biomass, compared to the mixture 50:20:30 PS-CB-MP. Regarding fertilization, both doses evaluated (7 g and 10 g) produced plants with statistically similar values of height, diameter, and shoot dry biomass. Finally, in the interaction of factors, treatment 7 (T7) produced plants with greater values of diameter, and shoot, root, and total dry biomass (Table 3).

The *Quercus crassifolia* plants presented greater diameters than those of *Q. robur* L. evaluated by Devetaković et al. (2019) and produced in plastic containers of capacity 120 cm^3, which could be explained by the greater volume of the containers utilized in this study. Likewise, Popović et al. (2014) obtained *Q. robur* plants of greater dimensions and better quality in containers of 220 mL and 265 mL compared to those produced in containers of capacity 120 mL.

Siqueira et al. (2025) indicate that containers of greater size tend to favor greater survival and more rapid initial growth; however, when the quality of the plantation site is suitable, container size becomes less important for many species. For this reason, the authors recommend the use of large containers of between 150 and 310 mL in volume as an efficient option in terms of cost-benefit ratio. In the present study, the use of the larger container (200 mL) had a positive effect on plant growth since the plants showed higher values of height and diameter than those reported by Jokanović et al. (2024) in *Q. robur*, *Q. petraea* Matt. Liebl. and *Q. frainetto* Ten. grown in Bosnaplast 18 plastic containers of capacity 220 mL. *Quercus robur* had the highest values of diameter (4.37 mm), followed by *Q. frainetto* (3.65 mm), while *Q. petraea* presented the lowest values (3.0 mm). It should be noted that each species has different growth habits and therefore responds differently to the size of the containers used in the two studies.

To achieve successful reforestation in the degraded forests of Mexico, it is essential to meet several key criteria, including the appropriate selection of species and the use of plants with high-quality morphological parameters, especially in terms of stem height and diameter. In the case of the genus *Pinus*, these parameters are well defined for Mexican species at the nursery stage (age 6 to 18 months, height 12 to 30 cm, and diameter greater than 4.0 mm) (Secretaría de Economía 2016); however, for *Quercus*, these parameters are only specified for seven of the 170 species reported for Mexico, and *Q. crassifolia* has not been included. Nevertheless, in this study, the plants in all treatments presented diameters greater than those recommended for these *Quercus* species (greater than 4 mm).

Table 2. Results of the ANOVA for the effects of substrate, container, and fertilization on the morphological parameters and quality indices in *Quercus crassifolia* produced in a nursery with different containers, substrates, and doses of fertilizer.

Variables	Factors	Mean Sq	Valor F	Valor P
Height (cm)	Substrate	63.78	21.31	< 0.0001 ***
	Container	50.46	16.60	< 0.0001***
	Fertilization	6.50	2.03	0.155 ns
	Interaction	17.01	5.95	< 0.0001 ***
Diameter (mm)	Substrate	2.23	4.34	0.038 *
	Container	0.01	0.01	0.905 ns
	Fertilization	0.06	0.12	0.729 ns
	Interaction	1.17	2.32	0.0257 *
Shoot dry biomass (g)	Substrate	3.89	34.72	< 0.0001 ***
	Container	0.01	0.01	0.926 ns
	Fertilization	0.02	0.23	0.628 ns
	Interaction	0.73	6.71	< 0.0001 ***
Root dry biomass (g)	Substrate	2.65	6.36	0.0122 *
	Container	2.40	5.74	0.0172 *
	Fertilization	3.50	8.46	0.0039 **
	Interaction	1.79	4.60	< 0.0001 ***
Total dry biomass (g)	Substrate	12.97	16.43	< 0.0001 ***
	Container	2.50	3.02	0.0829 ns
	Fertilization	4.18	5.09	0.0248 *
	Interaction	4.10	5.47	< 0.0001 ***
Main root dry biomass (g)	Substrate	0.55	2.29	0.131 ns
	Container	0.03	0.15	0.698 ns
	Fertilization	1.67	7.04	0.00839 **
	Interaction	0.63	2.70	0.01 *
Secondary roots dry biomass (g)	Substrate	0.78	10.27	0.00151 **
	Container	1.84	25.42	0.0001 ***
	Fertilization	0.33	4.29	0.0392 *
	Interaction	0.49	7.20	< 0.0001 ***
Dickson quality index	Substrate	0.76	3.56	0.06 ns
	Container	0.06	0.31	0.575 ns
	Fertilization	1.57	7.40	0.0069 **
	Interaction	0.67	3.29	0.00219 **
Robustness index	Substrate	1.56	7.46	0.0067 **
	Container	2.53	12.30	0.000526 ***
	Fertilization	0.20	0.94	0.333 ns
	Interaction	0.77	3.86	0.0005 ***
Shoot to root ratio	Substrate	1.33	8.81	0.00325 **
	Container	0.23	1.49	0.223 ns
	Fertilization	2.05	13.84	0.00024 ***
	Interaction	0.59	4.11	0.000255 ***

*= p<0.05; **= p<0.01; ***= p<0.001; ns = not significant.

The results of this study align with those reported by Mariotti et al. (2020), who point out that the absence of a significant effect of fertilization in the early stages of growth of *Q. ilex* L. is more closely related to the size and nutritional content of the acorn than to the substrate condition. According to Villar-Salvador et al. (2009), the acorn provides the necessary nutrients to the plant until the onset of sprouting. In this context, the dose of 7 g L^{-1} applied in this study favored root system development, suggesting that this dose was sufficient to promote optimal root growth once the seed reserves were depleted.

Table 3. *Quercus crassifolia* morphological results (mean ± standard error) following growth in a nursery using different containers, substrates, and fertilizer doses.

Factor	Height (cm)	Diameter (mm)	Dry biomass (g)		
			Shoot	Root	Total
		Container			
CPOL-170 mL	8.3±0.29 b	4.6±0.12 a	1.1±0.06 a	1.3±0.09 b	2.4±0.14 a
CPLA-200 mL	9.2±0.27 a	4.6±0.12 a	1.1±0.05 a	1.5±0.11 a	2.6±0.15 a
		Substrate			
50:20:30 PS-CB-MP	8.3±0.27 b	4.5±0.11 b	1.0±0.05 b	1.3±0.09 b	2.3±0.13 b
25:25:50 PS-CB-MP	9.2±0.30 a	4.7±0.13 a	1.2±0.06 a	1.5±0.12 a	2.7±0.16 a
		Fertilizer dose			
7 g	8.6±0.27 a	4.6±0.12 a	1.1±0.05 a	1.5±0.11 a	2.6±0.15 a
10 g	8.9±0.30 a	4.6±0.12 a	1.1±0.05 a	1.3±0.10 b	2.4±0.14 b
Interaction					
T1: CPOL-170+50:20:30 +7 g	7.7±0.24 c	4.4±0.10 b	0.9±0.05 bc	1.3±0.09 b	2.3±0.14 b
T2: CPOL-170+50:20:30 +10 g	8.0±0.30 bc	4.7±0.13 ab	1.1±0.07 abc	1.2±0.08 b	2.3±0.13 b
T3: CPOL-170+25:25:50 +7 g	8.6±0.29 abc	4.8±0.15 ab	1.2±0.07 a	1.6±0.11 ab	2.8±0.16 ab
T4: CPOL-170+25:25:50 +10 g	9.1±0.35 ab	4.7±0.12 ab	1.1±0.05 abc	1.2±0.09 b	2.3±0.11 b
T5: CPLA-200+50:20:30 +7 g	8.7±0.27 abc	4.5±0.11 ab	0.9±0.05 bc	1.3±0.10 b	2.3±0.14 b
T6: CPLA-200+50:20:30 +10 g	8.7±0.25 abc	4.7±0.11 ab	0.9±0.04 bc	1.4±0.09 b	2.3±0.11 b
T7: CPLA-200+25:25:50 +7 g	9.5±0.26 a	4.9±0.10 a	1.3±0.05 a	1.9±0.13 a	3.2±0.17 a
T8: CPLA-200+25:25:50 +10 g	9.7±0.31 a	4.5±0.13 ab	1.2±0.07 ab	1.4±0.14 b	2.6±0.19 ab

Where: PS=pine sawdust, CB=composted bark, MP=moss peat. In each column, different letters for the same variable, per factor, denote significant differences (Tukey, $p < 0.05$)

Furthermore, the lower growth observed in all morphological variables in plants produced in the mixture containing a higher proportion of sawdust can be attributed to the high carbon/nitrogen (C:N) ratio, which is generally present in organic substrates such as fresh sawdust because of the high lignin and cellulose content (Mariotti et al. 2020). This characteristic can induce the immobilization of soluble nitrogen, reducing the availability of this essential nutrient for plant development. This suggests the need to increase the dose of controlled-release fertilizer or supplement it with nitrogen-rich water-soluble fertilizers to avoid deficiencies during the nursery stage (Dumroese et al. 2018; Madrid-Aispuro et al. 2020; Mariotti et al. 2020). Similar results have been reported in other studies that used high proportions of sawdust in substrates for nursery plant production (Barrett et al. 2016; González-Orozco et al. 2018; Madrid-Aispuro et al. 2020). For example, Mariotti et al. (2020) indicated that adequate fertilization can compensate for the chemical limitations of a coconut fiber-based substrate in the growth of *Q. robur*, *Q. pubescens* Willd., and *Q. ilex.*

Likewise, plants grown in substrates with a high percentage of peat presented greater height, diameter, and dry biomass components compared to those produced with a higher proportion of sawdust. Previous studies have reported similar results in Mediterranean species such as *Q. robur* and *Q. ilex* (Mariotti et al. 2020). In the case of Mexico, research has been documented on *Q. rugosa* (De Jesús et al. 2021), *Q. crassipes* (Venancio et al. 2022), and *Q. durifolia* (Madrid-Aispuro et al. 2025), in which different substrate mixtures were used. In all cases, moss peat and composted bark were common components, used in proportions of up to 60%. Fresh pine sawdust was only used (up to 33%) in the case of *Q. durifolia*, obtaining good results when supplemented with a dose of 10 g L^{-1} of controlled-release fertilizer (Multicote® 18-6-12 of NPK).

The diameter of the plants obtained in this study in both substrate mixtures was greater than that reported for *Q. rugosa* (3.5–4.5 mm) and *Q. crassipes* (3.6–4.3 mm) grown in containers with up to 48% moss peat (De Jesús et al. 2021; Venancio et al. 2022). Likewise, the values were comparable to those recorded by Madrid-Aispuro et al. (2025) for *Q. durifolia* (4.9–5.1 mm), produced in mixtures of moss peat, composted bark, and raw pine sawdust (S1 = 60:20:20, S2 = 50:25:25, and S3 = 33:33:33). However, in terms of height, the plants in this study presented lower values. This difference can be attributed to the age of evaluation in each case (*Q. durifolia*: 10 months, *Q. crassipes*: 7 months, *Q. rugosa*: 11 months), as well as the characteristic growth habit of each species. In the present study, the evaluation was carried out after nine months of growth in the nursery.

The interaction of the CPLA-200 container with the 25:25:50 substrate mixture (PS:CB:MP) and the 7 g fertilization dose promoted plant growth in all parameters evaluated (height, diameter, and shoot, root, and total dry biomass). The 7 g dose was sufficient to stimulate greater biomass production in the main root and promote the development of secondary roots (Figure 4). Del Campo et al. (2010) established quality standards for *Q. ilex*, indicating that foliar concentrations of nitrogen and phosphorus must exceed 1.0 and 0.9 mg g^{-1}, respectively, to improve post-transplantation performance. Similarly, Pascual et al. (2012) highlighted that a higher concentration of phosphorus in root tissue is key to stimulating root growth capacity after planting.

Mariotti et al. (2015b) demonstrated that the use of larger containers significantly promotes the growth of *Q. robur* seedlings, especially in terms of shoot and root development. Plants produced in containers larger than 4.5 liters showed greater total biomass, with more than 50% concentrated in the root system, where the taproot was the main component. In the genus *Quercus*, it is common for the main root to be longer, thicker, and to represent a greater proportion of the root system (Pemán and Gil 2008). It is also known as a lignotuber, which is a swollen woody structure located in the root-shoot transition zone that contains numerous dormant buds and starch reserves. This structure allows the plant to regrow prolifically after severe disturbances that eliminate shoot biomass or as a reaction to pruning (Paula et al. 2016). In this study, the larger volume container favored the development of a thicker main root and a greater number of secondary roots in the plants (Figure 4).

The analysis of variance showed significant differences in the Dickson quality index only in relation to the fertilization dose, as well as in the interaction with container type (Table 4). The plants evaluated in this study had a lower robustness index than that reported for *Q. robur* and *Q. crassipes* by Devetaković et al. (2019) and Venancio et al. (2022), respectively, who used plastic containers with volumes of 120 and 150 mL. This difference could be attributed to the larger volume of the containers used in the present study. The lowest robustness index value was observed in plants grown in the CPOL-170 mL container, combined with a mixture with a high proportion of sawdust and both fertilizer doses. The lower height growth recorded in that treatment acted to reduce the value of the index.

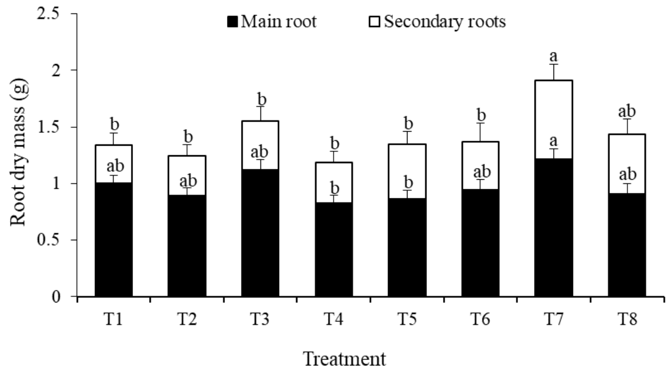

Figure 4. Root dry biomass of the plants per treatment. Bars represent the standard error. Different letters for the same variable denote significant differences among treatments (Tukey, $p < 0.05$).

The best average value of the Dickson quality index was obtained in treatment T7: CPLA-200 + 25:25:50 + 7 g, indicating a significant effect of container type, the mixture with a high proportion of peat, and the lower fertilizer dose on the morphological growth variables (Table 4). The Dickson quality index reached values higher than those recommended by Aldrete et al. (2023) for broadleaf species, and also higher than those reported for *Q. cerris* L. (0.2) by Bilgin (2019) and *Q. rugosa* by De Jesús et al. (2021), who used substrates composed of vermiculite (36%), perlite (16%), and moss peat (48%) in containers of 93, 135, and 210 cm^{-3} (0.3, 0.5, and 0.6, respectively). However, Popović et al. (2024) reported higher Dickson quality index values for *Q. robur* (1.45-1.86), possibly due to the use of containers of greater volume (390 cm^{-3}).

The shoot/root ratio (SRR) was less than 2.5 in all treatments, which is the recommended value for broadleaf species grown in containers (Aldrete et al. 2023b). Tsakaldimi and Ganatsas (2016) reported a higher shoot/root ratio in one-year-old plants of *Q. macrolepis* Kotschy and *Q. ilex* grown in mixtures of peat and coconut fiber, compared to those produced in peat with perlite. Venancio et al. (2021) evaluated substrates composed of pine bark, vermiculite, and perlite (60:30:10), fertilized with 3 kg m^{-3} of Osmocote® 15-9-12 NPK, without observing significant effects on the shoot/root ratio. Mariotti et al. (2020) found that the use of potassium-enriched peat promoted greater root development, with the shoot/root ratio remaining below 1 in all cases. These authors also noted that coconut fiber reduced this ratio, especially in *Q. pubescens.*

A low shoot/root ratio has been associated with higher survival under drought conditions in *Quercus* species (Del Campo et al. 2010). However, Villar-Salvador et al. (2004) reported the opposite: *Q. ilex* plants with a higher shoot/root ratio showed lower mortality and higher growth in the field compared to those with lower ratios (0.63). In the present study, the values ranged from 0.7 to 1.1, were similar among the factors evaluated, and coincide with the values reported by Venancio et al. (2021) for *Q. crassipes* (0.9–1.0) and Mariotti et al. (2020) for *Q. ilex* (0.71).

Table 4. Quality indices of *Quercus crassifolia* plants (mean ± standard error) produced in nurseries using different containers, substrates, and fertilization rates.

Factor	Dickson quality index	Robustness index	Shoot to root ratio
Container			
CPOL-170 mL	1.00±0.08 a	1.8±0.08	0.9±0.06
CPLA-200 mL	1.00±0.08 a	2.0±0.07	0.8±0.07
Substrate			
50:20:30 PS-CB-MP	0.90±0.07 a	1.9±0.07	0.8±0.05
25:25:50 PS-CB-MP	1.00±0.08 a	2.0±0.08	0.9±0.07
Fertilizer dose			
7 g	1.10±0.08 a	1.9±0.08	0.8±0.05
10 g	0.90±0.07 b	2.0±0.07	1.0±0.08
Interaction			
T1: CPOL-170+50:20:30 +7 g	1.00±0.07 ab	1.8±0.07	0.7±0.03
T2: CPOL-170+50:20:30 +10 g	0.93±0.07 ab	1.7±0.07	0.9±0.07
T3: CPOL-170+25:25:50 +7 g	1.10±0.09 ab	1.9±0.09	0.9±0.06
T4: CPOL-170+25:25:50 +10 g	0.83±0.07 b	1.9±0.07	1.1±0.07
T5: CPLA-200+50:20:30 +7 g	0.90±0.07 b	2.0±0.07	0.8±0.05
T6: CPLA-200+50:20:30 +10 g	0.91±0.06 b	1.9±0.07	0.8±0.07
T7: CPLA-200+25:25:50 +7 g	1.30±0.09 a	2.0±0.07	0.8±0.06
T8: CPLA-200+25:25:50 +10 g	0.90±0.08 b	2.2±0.09	1.0±0.10
*Recommended values	≥ 0.5	≤ 7.5	≤ 2.5

Where: PS=pine sawdust, CB=composted bark, MP=moss peat. *Source: Aldrete et al. (2023). Different letters for the same variable denote significant differences among treatments (Tukey, $p < 0.05$).

The results obtained show that container size, substrate composition, and fertilization dose significantly influence the morphological indicators of plant quality in *Quercus crassifolia*. However, it is not possible to establish a uniform response for the genus *Quercus* since the results vary between species. Further research is therefore required to optimize the growth of each species.

4 Conclusions

This study demonstrated that substrate mixtures, containers, and fertilization doses influence the nursery production of *Quercus crassifolia* seedlings. The cultivation of *Quercus crassifolia* in 200 mL containers, using a mixture comprising 25 % sawdust, 25 % composted bark, and 50 % peat moss, together with the application of 7 g L^{-1} of controlled-release fertilizer, produced seedlings of greater height, diameter, above-ground dry biomass, root dry biomass, and total dry biomass, as well as a higher Dickson quality index. The use of alternative substrates, such as sawdust and composted bark, represents a viable and locally accessible option that effectively promotes the growth of *Quercus crassifolia* in nurseries.

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