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Effects of container size and growing media on growth of argan (*Argania spinosa*) seedlings in Morocco

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Abstract

Background: Argan (*Argania spinosa*) is an important arid species in Morocco, hence the need to undertake nursery practices that promote its regeneration and sustainability in a vulnerable environment. This study aimed to examine the effect of container size and growing medium on morphological traits, biomass, as well as root morphology of one-year-old argan seedlings in the Marrakech region of Morocco.

Methods: Three container sizes of 300, 400, and 500 cm^3 were selected in which seven types of growing media with varying proportions of acacia compost, crushed cypress cones, Barbary thuja, eucalyptus capsule composts, and potting soil were used. Subsequently, measurements of plant growth variables and biomass, as well as identification of root deformations were carried out.

Results: Our results show that container size and growth medium strongly influenced ($p < 0.001$) morphological traits and biomass of argan seedlings. Growth was highest in seedlings grown in the 500 cm^3 container on substrates composed of both 100% acacia compost and 50% potting soil + 50% acacia compost, while it was lowest in seedlings in the 300 cm^3 container with the compost composed of a mixture of equal proportions of cypress and Barbary thuja, and eucalyptus. While the main root deformities were hooked roots (14.1%) and root eccentricity (13.0%), seedlings with multiple deformities were by far the most common (38.4%). The size of the container did not seem to influence their occurrence, whereas about 35% of the deformations were observed in seedlings grown on substrates composed of mixtures of potting soil and acacia compost, cypress cones, and Barbary thuja and eucalyptus composts.

Conclusions: This study shows the importance of adopting an adequate protocol to allow the regeneration of forest species with the necessary characteristics to survive the often-challenging environmental conditions prevailing not only in southern Morocco but also across most of the country.

Keywords: *Argania spinosa*; Container size; Forest nursery; growing medium; seedling quality; root architecture

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Introduction

The argan tree (*Argania spinosa*) represents the second most important Moroccan forest species by area, spanning about 951 910 ha, although a significant part of its ecosystem is composed of low-density stands (HCEFLCD 2022). This highly adaptable species is endemic to southwest Morocco and plays an important ecological and socio-economic role in a region dominated by arid conditions. With a lifespan that can vary between 300-350 years, the argan tree has a wide range of uses for the local population: Argan wood and fruit husks are used as fuel for heating; the leaves and fruit pulp provide valuable fodder for livestock; the thorny branches are used as fencing for agricultural plots; the seeds are used to produce edible oil and cosmetics; while, the rich soil that characterises its stands is very favourable to intercropping, favouring agroforestry systems (Boudy 1950; M'Hirit et al. 1998; Defaa et al. 2015).

However, argan trees are experiencing degradation due to human activities, such as increased fruit harvesting, despite a long history of human dependence on the species (Faouzi 2018). This surge in demand for argan oil reduces natural regeneration of argan trees (Bellefontaine et al. 2010). In addition, climate change, particularly declining rainfall, further hinders natural argan tree regrowth (El Ghazali et al. 2021). Although forest managers have attempted to address this problem through artificial regeneration for over a decade, these reforestation efforts often have limited success (Belghazi et al. 2020). This suggests that both unfavourable field conditions and potentially inadequate nursery practices may be contributing to these low survival rates.

Seedling quality directly impacts post-planting performance, influencing survival under stress and promoting healthy growth (Grossnickle & MacDonald 2018). Fast initial growth is crucial for forest establishment success, especially in degraded areas like argan forests where slow growth and high seedling mortality are challenges (Close et al. 2010; Aghai et al. 2014; Tian et al. 2017). Seed dormancy, often worsened by water stress, further complicates restoration in these areas (Trobat et al. 2011; Puértolas et al. 2012). Seedling height, root collar diameter, and leaf area are commonly used to assess quality due to their correlation with seedling biomass and ease of measurement (Chirino et al. 2009; Grossnickle 2012; Ivetić et al. 2016; Nyoka et al. 2018). Cultural practices like container selection, medium choice, pruning, and fertilisation can improve seedling performance (Carles et al. 2012; Bakry et al. 2013).

Container characteristics (size, depth, diameter) significantly impact seedling quality, particularly root development (Chirino et al. 2008; Kostopoulou et al. 2011). While depth is crucial for water holding, temperature, and aeration (Chirino et al. 2008), diameter also influences root growth and water distribution (Tian et al. 2017). In dry environments, deep containers promote a well-structured root system for better water uptake (Tsakaldimi et al. 2009). Alongside suitable containers, an ideal growing medium is essential for supporting seedlings, retaining water, and providing oxygen and nutrients (Jaenicke 1999; Bayala et al. 2009; Nyoka et al. 2015). Forest nurseries often lack consistent access to forest soil, leading to mineral substrates that can hinder growth (M'Sadak et al. 2012). Composting offers a promising alternative, promoting the decomposition of organic matter and stabilizing organic substrates (Fitzpatrick 2001; Duong et al. 2012; Ndiaye et al. 2018).

In this context, the present study aims to highlight the influence of rigid containers of different volumes, as well as the growing substrate on the characteristics and, therefore, the performance of young argan seedlings in nursery. The specific objectives were to evaluate the effect of three container sizes of 300 cm^3, 400 cm^3, 500 cm^3 in volume, as well as seven types of substrates based on composts of acacia (*Acacia cyanophylla*), crushed cones of cypress, Barbary thuja and eucalyptus capsules, and potting soil on the morphometric traits and biomass of argan seedlings. In addition, the root system architecture of the seedlings was evaluated, and the frequency of root deformations recorded. Overall, this work aimed to propose an appropriate technical guide for raising quality argan seedlings for planting and reforestation in the region.

Methods

Study site

The study was carried out in the nursery belonging to the Regional Center of Forestry Research in Marrakech (CFRM), located 2.5 km northeast of the city of Marrakesh, Morrocco. The bioclimate is semi-arid, with a mean annual precipitation of 240 mm. The mean maximum of the hottest month (August) is 38.3°C, while the mean minimum of the coldest month (January) is 4.5 °C. The nursery is located at an elevation of 412 m on flat terrain.

Plant material and experimental design

The seeds used in this study were collected from the El Hanchane region (31°27'34" N, 9°29'31" W), which is considered one of the genetically best provenances of the Argan tree. The collection was carried out during the months of June and July, which corresponds to the ripening period of the Argan fruits. The nuts were collected from at least ten trees.

Their nursery culture study was conducted over a 12-month period. A completely randomized design was used consisting of three types of honeycomb containers (Table 1) and growing media based on seven types of substrates including: (i) S1: 100% potting soil; (ii) S2: 100% acacia compost; (iii) S3: a mixture of equal proportions of cypress and Barbary thuja cones, and eucalyptus capsules compost; (iv) S4: 50% S1 + 50% S2; (v) S5: 50% S1 + 50% S3; (vi) S6: 25% S1 + 75% S2; and (vii) S7: 25% S1 + 75% S3. Once the seedling substrate mixtures were prepared, they underwent a four-month composting cycle with regular turning until the compost matured. These composts were chosen because they can be produced satisfactorily to meet the needs of local forest nurseries in Morocco and can be an alternative

TABLE 1. Characteristics of containers used for seedling growth

Container	Number of cavities	Upper section of cavity (cm^2)	Lower section of cavity (cm^2)	Base section (cm^2)	Height of cavity (cm)	Base height (cm)	Volume (cm^3)
P28	28	47.61	17.50	4.41	15.00	1.50	500
P38	38	29.16	16.40	2.89	17.50	2.50	400
P54	54	25.00	12.25	2.89	17.00	2.50	300

to imported and expensive peat-based substrates (Ferradous et al. 2017).

The experiment comprised 21 treatments (3 containers x 7 substrates), with each treatment replicated four times to minimise error to an acceptable threshold (Dagnelie 1986). The experimental layout is shown in Figure A1. A total of 2,100 argan seedlings were sown, with 25 seeds per treatment.

Container potting was carried out manually to ensure normal and uniform substrate compaction in all cavities, especially those in the corners of the container. Sowing was done directly into the cavities, to a depth of one centimetre (Figure A1). Irrigation was provided regularly (every evening) using an automated sprinkler system. No fertiliser was applied during the plant growth season.

Substrate analyses

To understand the influence of growing media on plant growth, the physicochemical properties of the corresponding substrates were assessed. Specifically, the analyses of physical properties performed included the determination of particle size distribution, bulk density, microporosity, macroporosity and, consequently, total porosity, in accordance with the methodology established by Lamhamedi et al. (2006). The chemical properties analyses focused on: (i) pH measurement, conducted on a suspension containing 10 mL of substrate and 20 mL of distilled water; (ii) electrical conductivity assessed in a suspension composed of 10 mL of substrate and 40 mL of distilled water; (iii) organic carbon content determined by cold oxidation using potassium dichromate in an acidic medium; (iv) total nitrogen quantified using the Kjeldahl method; (v) assimilable phosphorus extracted by the Olsen method; and (vi) exchangeable potassium extracted with sodium hexametaphosphate. More detailed on the methods used are given in the works of Anne (1945), Olsen (1954), and Bremner (1960). Analyses were performed on samples collected before sowing, with 3 samples per substrate type.

Evaluation of seedling characteristics

Morphological traits

At the end of nursery culture, following 12 months of growth, 15 plants per treatment (totalling 315 plants) were randomly selected for the evaluation of morphometric traits, including height, root variables, and leaf surface area (LSA). Both seedling height and the length of the taproot were measured using a ruler graduated in cm, while root-collar diameter (RCD) was measured using callipers set to the nearest tenth of a millimetre. In addition, the number of lateral secondary roots per taproot was recorded. LSA was determined by equating the leaf shape to an ellipse and was, therefore, calculated based on the following equation:

$$LSA\ (mm^2) = \pi/4 * L * l$$

where, L represents the maximum length of the leaf (mm), while l is the maximum width of the leaf (mm).

Biomass measurement

Following the measurement of the seedling morphological traits, the dry biomass of both above-ground and root sections of seedlings were determined. The length of the drying period was determined based on a test to monitor the moisture content of five seedlings of different sizes, chosen at random among the plants from the different treatments. The results of this monitoring showed that a duration of 24 hours in an oven at 60 °C was largely sufficient to eliminate excess water from the plants. Thus, following the drying of the seedlings, the separation of the above-ground and root of the plants was carried with the help of secateurs. Subsequently, measurements of the following traits were carried out on all 315 selected seedlings: (i) total above-ground dry biomass; (ii) total belowground dry biomass; (iii) stem dry biomass; (iv) leaf dry biomass; (v) taproot dry biomass; and (vi) root hairs dry biomass. These measurements were conducted using a scale with an accuracy of 0.0001 g.

Root system architecture

Root system diagnosis aims to detect the possible presence of root deformations, which are one of the major drawbacks of containerised plants (Lindström & Rune 1999; Sung et al. 2019). This diagnosis was carried out before the disposal of the associated seedling and consisted of the following: (i) locating the different types of root deformations; (ii) identifying the different root deformations; (iii) drawing the taproot of each seedling relative to the nursery treatments studied; and (iv) examining the effect of the both container size and growing medium on the root deformations.

Data analyses

Two-way analysis of variance (ANOVA) was used to investigate the relationship between seedling morphological traits (height, RCD, LSA) and biomass (leaves and roots), and container type and growing substrate. Subsequently, Newmans-Keuls tests were performed post hoc for multiple comparisons of container and substrate groups. The significance level of the statistical tests was $p < 0.05$. As for the evaluation of the influence of container size and growing medium on the architecture of the root system, a simple analysis of the frequency (percentage) of occurrence of root deformations on seedlings was performed.

Results

Properties of the growing media

The results of the physical analyses are presented in Table 2 while those of the chemical analyses are presented in Table 3. Bulk density ranged between 0.18 and 1.32 g/cm^3 recorded for the 100% acacia-based compost (S2) and 100% potting soil (S1) mediums, respectively. Correspondingly, total porosity, which decreases with increasing bulk density, was lowest for substrate S1. Conversely, it was highest for substrates S3 (100% compost based on a mixture of cypress, Barbary thuja, and eucalyptus) and S2 at 62.39 ± 0.31% and 56.80 ± 0.86%, respectively, which had the two lowest observed bulk densities.

The results of the chemical analyses show that the pH of the substrates used ranged from 6.38 to 8.83, corresponding to substrates S2 (100% acacia-based compost) and S1 (100% potting soil), respectively, which were mostly below the adequate levels required for the growth of argan trees. On the other hand, electrical conductivity showed large variations, ranging from 0.16 ± 0.01 mS/cm to 3.38 ± 0.02 mS/cm, recorded under S1 and S2 substrates, respectively. Organic matter was by far the lowest in the 100% potting soil-based substrate (S1) with 1.28 ± 0.04%, while the richest substrate was S3 (100% compost based on a mixture of cypress, Barbary thuja and eucalyptus), having levels up to 47.52 ± 0.20%. Substrate S1 had the lowest macronutrient content in the soil, with values of 0.05 ± 0.01%, 1.89 ± 0.03 mg/100g and 18.94 ± 0.80 mg/100g corresponding to nitrogen, phosphorus and potassium respectively. Conversely, substrates S2 and S3 were the richest in macronutrients.

Morphological traits and biomass of seedlings

The results of the two-way ANOVA to investigate the effect of container type and growing medium on morphological traits and, consequently, on the biomass of argan seedlings are reported in Table 4. Seedling height, LSA, leaf dry biomass and root biomass were very strongly influenced ($p < .001$) by container size. It also had a significant effect on RCD but this was not as strong ($p < .01$). Growth medium had a very strong influence on morphological traits and seedling biomass. In addition, highly significant interactions between of container and growth medium were observed on all measured parameters, indicating that the joint effect of substrate and container is still evident on growth variables and thus the need to study each factor separately.

As a result of the very highly significant effect of both container type and growing medium on seedling growth, Newman-Keuls tests were conducted post hoc, and the results are presented in Tables 5-7. Some caution should be exercised when interpreting the main effects of container size and growing medium on seedling traits, given that the presence of a statistically significant interaction between container size and growing medium. The 300 cm^3 (P54) and 400 cm^3 (P38) containers were observed to have a similar influence on argan seedlings. Moreover, they were characterized by the lowest quality seedlings. Conversely, the 500 cm^3 (P28) container yielded the highest quality seedlings. These had an average height, RCD, LSA, total above-ground biomass, and total root biomass of 16.7 ± 7.27 cm, 4.23 ± 0.77 mm, 46.01 ± 35.09 mm^2, 0.67 ± 0.58 g, and 0.16 ± 0.11 g, respectively.

Post-hoc tests corresponding to the effect of substrate on seedling morphological traits identified four distinct groups of substrates in relation to seedling height. The substrates least favourable for height growth were S7 (25% potting soil + 75% mixture of cypress, Barbary thuja and eucalyptus compost) and S3 (100% mixture of cypress, Barbary thuja and eucalyptus compost), while those with the best growth conditions were S2 and S4, which resulted in seedlings with an average height greater than 19 cm. Five distinct groups of substrates were observed with respect to RCD growth. Substrate S3 yielded seedlings with the lowest RCD (3.44 mm), while S4 yielded the seedlings with the highest RCD (4.75 mm).

TABLE 2. Physical properties of substrates used in the experiment.

Substrate	n	Bulk density (g/cm^3)	Macroporosity (%)	Microporosity (%)	Total porosity (%)
S1	3	1.32 ± 0.00	7.38 ± 0.19	18.45 ± 0.39	25.83 ± 0.44
S2	3	0.18 ± 0.01	28.56 ± 0.93	28.24 ± 0.19	56.80 ± 0.86
S3	3	0.20 ± 0.01	36.96 ± 0.24	25.43 ± 0.46	62.39 ± 0.31
S4	3	0.78 ± 0.03	18.52 ± 0.19	22.41 ± 0.44	40.93 ± 0.37
S5	3	0.80 ± 0.04	23.62 ± 0.37	20.04 ± 0.37	43.66 ± 0.07
S6	3	0.49 ± 0.03	26.64 ± 0.19	26.28 ± 0.51	52.92 ± 0.55
S7	3	0.50 ± 0.02	31.21 ± 0.49	23.22 ± 0.72	54.43 ± 0.31

TABLE 3. Chemical properties of substrates used in experiment

Substrate	**n**	**Chemical property**							
		pH	EC (mS/cm)	OM (%)	C (%)	N (%)	C/N	P (mg/100 g)	K (mg/100 g)
S1	3	8.83 ± 0.01	0.16 ± 0.01	1.28 ± 0.04	0.75 ± 0.02	0.05 ± 0.01	15.44 ± 2.28	1.89 ± 0.03	18.94 ± 0.80
S2	3	6.38 ± 0.02	3.38 ± 0.02	42.20 ± 0.18	24.53 ± 0.10	1.10 ± 0.03	22.38 ± 0.59	11.09 ± 0.07	203.90 ± 0.11
S3	3	7.90 ± 0.02	0.83 ± 0.01	47.52 ± 0.20	27.63 ± 0.11	0.95 ± 0.04	29.19 ± 1.20	12.01 ± 0.04	268.38 ± 2.69
S4	3	7.44 ± 0.01	1.68 ± 0.01	21.68 ± 0.17	12.61 ± 0.10	0.53 ± 0.02	23.61 ± 0.64	6.30 ± 0.08	106.49 ± 0.11
S5	3	8.15 ± 0.01	0.32 ± 0.01	23.65 ± 0.15	13.75 ± 0.09	0.47 ± 0.02	29.21 ± 1.25	7.35 ± 0.06	125.50 ± 1.09
S6	3	7.18 ± 0.01	2.77 ± 0.01	32.19 ± 0.19	18.71 ± 0.11	0.80 ± 0.02	23.33 ± 0.73	8.40 ± 0.06	145.32 ± 1.90
S7	3	8.02 ± 0.02	0.55 ± 0.01	36.17 ± 0.14	21.03 ± 0.08	0.70 ± 0.03	30.08 ± 1.29	9.36 ± 0.06	186.01 ± 1.67

n: number of samples EC: electrical conductivity; OM: organic matter; C: carbon; N: nitrogen; P: plant available phosphorus; K: plant available potassium

Similarly, five distinct substrate groups were observed in relation to LSA, with seedlings with the smallest LSA produced under S3 (12.72 ± 7.17 mm^2). Conversely, substrate S2 produced seedlings with the largest LSA with an average of 59.60 ± 25.99 mm^2.

Three distinct substrate groups with respect to leaf dry biomass were observed, with S2, S4, and S6 showing the most ideal conditions for above-ground biomass development. In fact, these were the only substrates to produce seedlings with an average dry biomass greater than 0.5 g. Conversely, S3 produced seedlings with the smallest leaf biomass, with an average of 0.18 g. Four distinct substrate groups were recorded with respect to root biomass. Consistent with the observations on leaf biomass, substrates S2, S4, and S6 had seedlings with the highest average root biomass. In contrast, substrate S1 was the least favourable for belowground biomass development, highlighted by seedlings with an average root biomass below 0.10 g.

Root system architecture of seedlings

The description and diagnosis of the root system (Table 8; Figure A3) highlighted important deformations with potential detrimental effects on the survival of the seedlings in the field. Except for seedlings presenting roots with multiple deformations (38.4%), the most prevalent deformations were S-shaped taproots (8.5%), root eccentricity (13.0%) and crook roots (14.1%).

Evaluation of the frequency of occurrence of root deformations as a function of container type and growing medium showed very little influence of either (Table 9). Indeed, seedlings grown in the different containers had almost identical occurrences of deformations, with frequencies ranging from 32.2% to 33.9%. Across the different growing media, the frequencies of root deformations ranged from 11.3% to 17.5%. The potting soil substrate had the seedlings with the least deformations, while substrates S5 (50% potting soil + 50% compost composed of a mixture of cypress, Barbary thuja and eucalyptus) and S7 (25% potting soil + 75% compost composed of a mixture of cypress, Barbary thuja and eucalyptus) yielded seedlings with the highest frequencies of deformations.

Discussion

In this study, the investigation of the effect of container size and growing medium on seedling quality revealed very strong influences of both treatments on morphological traits of argan seedlings and consequently on biomass. Container size had highly significant effects on the morphological traits (height, RCD, LSA) assessed and on seedling biomass, with the most desirable traits observed on seedlings grown in the 500 cm^3 containers. Conversely, the least desirable seedlings were obtained from the smallest, 300 cm^3 containers. Container effect on nursery-grown seedlings is well documented in the literature; the interaction between the physical characteristics of a container and seedling biology has been noted by various authors (Tsakaldimi et al. 2009; Poorter et al. 2012; Montagnoli

TABLE 4. Effect of container and substrate on seedling morphological traits and biomass

	Effect (F_{obs})		
	Container	**Substrate**	**Container × Substrate**
H	11.037***	28.945***	4.215***
RCD	6.190**	24.098***	5.223***
LSA	19.528***	51.651***	5.389***
Total above-ground biomass	8.417***	26.721***	5.767***
Total root biomass	8.864***	12.008***	5.318***

H : height; RCD : root collar diameter; LSA : leaf area; * : significant effect (α = 5 %) ; ** : highly significant effect (α = 1 %) ; *** : very highly significant effect (α = 0,1 %).

TABLE 5. Comparison of means of seedling morphological traits and biomass by container type.

Container	n	H (cm)	RCD (mm)	LSA (mm^2)	Total above-ground biomass (g)	Total root biomass (g)	Group	
P28	105	16.7 ± 7.27	4.23 ± 0.77	46.01 ± 35.09	0.67 ± 0.58	0.16 ± 0.11	A	
P38	105	13.6 ± 7.38	4.03 ± 0.77	32.17 ± 24.78	0.51 ± 0.48	0.12 ± 0.10		B
P54	105	13.5 ± 6.74	3.94 ± 0.77	29.16 ± 21.88	0.45 ± 0.33	0.11 ± 0.11		B

n: number of samples; H : height; RCD : root collar diameter; LSA : leaf area

TABLE 6. Comparison of means of seedling morphological traits by substrate

Parameter	Substrate	n	Mean	Groups				
Height (cm)	S2	45	19.4 ± 5.58	A				
	S4	45	19.1 ± 8.14	A				
	S6	45	17.4 ± 6.49	A	B			
	S1	45	15.7 ± 6.76		B			
	S5	45	12.4 ± 6.75			C		
	S7	45	9.8 ± 3.84				D	
	S3	45	8.4 ± 2.66				D	
RCD (mm)	S4	45	4.75 ± 0.79	A				
	S2	45	4.42 ± 0.57		B			
	S6	45	4.24 ± 0.84		B	C		
	S1	45	4.09 ± 0.75			C		
	S5	45	3.79 ± 0.62				D	
	S7	45	3.74 ± 0.52				D	
	S3	45	3.44 ± 0.45					E
LSA (mm^2)	S2	45	59.60 ± 25.99	A				
	S4	45	56.79 ± 33.12	A				
	S6	45	48.52 ± 33.28		B			
	S1	45	28.22 ± 17.64			C		
	S5	45	26.23 ± 19.59			C	D	
	S7	45	20.36 ± 12.39				D	
	S3	45	12.72 ± 7.17					E

n: number of samples; H : height; RCD : root collar diameter; LSA : leaf surface area

TABLE 7. Comparison of means of seedling biomass by substrate

	Substrate	n	Mean	Groups			
AB (g)	S2	45	0.89 ± 0.42	A			
	S4	45	0.88 ± 0.59	A			
	S6	45	0.77 ± 0.57	A			
	S7	45	0.45 ± 0.35		B		
	S5	45	0.35 ± 0.24		B	C	
	S1	45	0.30 ± 0.25		B	C	
	S3	45	0.18 ± 0.09			C	
RB (g)	S4	45	0.19 ± 0.12	A			
	S6	45	0.17 ± 0.13	A	B		
	S2	45	0.15 ± 0.11	A	B		
	S7	45	0.14 ± 0.08		B		
	S5	45	0.13 ± 0.09		B	C	
	S3	45	0.10 ± 0.07			C	
	S1	45	0.06 ± 0.05				D

n: number of samples; AB: total above-ground biomass; RB: total root biomass

et al. 2022). Among the characteristics affected are the rates of lateral root emission. Indeed, Montagnoli et al. (2022) observed seedlings with more than twice the number of lateral roots in large containers than those from small containers. The importance of lateral roots lies in their ability to help trap water in the surface soil and is a particularly important characteristic of argan seedlings as it promotes post-planting establishment in the field (Ain-Lhout et al. 2016). Container size has also been shown to affect root size and length, and plays a key role in the development of taproot deformations due to growth limitations. Indeed, vertical root growth is often limited by container size and depth, with a prevalence of circling roots as well as taproot deformations (S-shape, L-shape) observed in seedlings grown in small containers (Mathers et al. 2007; Benamirouche et al. 2020). This not only impacts root architecture but also has a negative effect on aerial plant parameters. Conversely, large containers are known to promote growth, providing an advantage to transplanted seedlings under dry soil conditions (Villar-Salvador et al. 2012).

Consistent with the observations on container size, the growing medium had a very highly significant effect on morphological traits and, consequently, on the biomass of argan seedlings. Specifically, substrates composed of 100% acacia compost (S2), as well as substrates

TABLE 8: Types of root system deformations observed in seedlings

Deformation type	Incidence (%)
Crook roots	14.1
Twisting of the taproot	1.7
Nodes at root collar	1.7
Root eccentricity	13.0
Formation of angle of about 110° with the stem	5.1
Upwards bending of lateral roots	7.3
J-shaped taproot	5.1
S-shaped taproot	8.5
L-shaped taproot	5.1
Multiple deformations	38.4

TABLE 9: Proportion of seedlings with root deformations by container and substrate

Parameter		Incidence of deformation (%)
Container	P28	33.9
	P38	32.2
	P54	33.9
Substrate	S1	11.3
	S2	14.1
	S3	13.6
	S4	13.0
	S5	17.5
	S6	13.0
	S7	17.5

composed of a mixture of acacia compost and potting soil (S4) in equal proportions promoted better seedling growth, with the highest (shoot and root) biomass observed for the corresponding argan seedlings. The results are in agreement with those reported by different authors (Saoudi 2005; Nahidi 2006; Benamirouche & Chouial 2018), who highlighted the beneficial effect of the mixed acacia compost - potting soil substrate on the behaviour of cork oak (*Quercus suber*) seedlings. Surprisingly, acacia-based compost has also been shown to produce better quality seedlings than forest humus. Indeed, Benamirouche and Chouail (2018) recorded better results in the quality of cork oak seedlings when comparing the two media, with seedlings produced from acacia compost showing significant growth gains with respect to height, RCD and biomass.

The analyses of the physio-chemical properties of the growing media underlined the favourable conditions under the S2 and S4 media, consisting respectively of acacia compost and potting soil. Total porosity, particularly for the 100% acacia-based compost, was among the highest at 56.8% which is the standard (50% < total porosity > 60%) recommended for seedling production as it allows adequate aeration and more efficient retention of water and nutrients while minimizing substrate leaching (Lamhamedi et al. 2006). The fibrous nature of substrates composed of acacia compost has also been noted by Laâbou (2009) and Chouial and Benamirouche (2022) who observed increased high water retention capacity of the substrate. On the other hand, pH (6.38 for S2; 7.44 for S4) fell within the near-neutral range and was similar to the values obtained by Ammari et al. (2003) and Benamirouche and Chouial (2018), who pointed this being the desirable range for out-of-soil nursery culture. Acacia compost, generally characterised by a high carbon to nitrogen ratio, provides a slow-release nitrogen source, mimicking natural conditions and promoting efficient root uptake, potentially favouring root development and biomass allocation towards roots (Brito et al. 2011; Brito et al. 2015). Moreover, its derived mulch can harbour beneficial mycorrhizal fungi that can potentially colonise argan roots (Hashem et al. 2016), enhancing nutrient uptake particularly phosphorus, crucial for seedling growth in nutrient-limited Mediterranean ecosystems. Conversely, the substrates consisting of composts derived from ground mixtures of cypress cones, Barbary thuja and Eucalyptus capsules exhibited the highest pH values and consequently had plants with the least desirable morphological traits and biomass. Both low (acidic) and high (basic) pH are known to hinder seedling development, with slow growth rates attributed to reduced photosynthetic efficiency (Tessmer et al. 2013; Dighton & Krumins 2014). Moreover, high pH tends to negatively affect the availability and absorption of mineral elements in the rhizosphere (Comtois et al. 2004; Lamhamedi et al. 2006; Sellal, 2016). Nonetheless, Eucalyptus can offer a quick nitrogen boost, stimulating initial growth and leaf development, likely impacting biomass allocation towards shoots (Downer & Faber 1995; Valenzuela-Solano 2003). In addition, it is associated with low allelopathic potential, therefore limiting seedling growth suppression (Heidari 2022). Other key soil elements that are useful for plant growth and whose uptake can be affected by soil pH include nitrogen, potassium and phosphorus. Consistent with favourable pH, they were among the highest recorded in this study under substrates composed primarily of acacia-based compost.

Interestingly, our investigation revealed that container size and growing medium had minimal impact on the root architecture of argan seedlings. This could be attributed to the limited range of container sizes used, possibly not constraining the root development of young argan seedlings, which might not have had fully developed root systems yet (Haase 2008). Moreover, compensatory growth within the containers could have obscured any potential disparities. Additionally, if all compost types supplied adequate nutrients, argan seedlings might not have needed to extensively explore the available space for resources, resulting in similar root architecture across different media. Another possible explanation could be the dominant influence of the seedlings' inherent genetic makeup on their root development patterns (Harrington et al. 2001; Raviteja et al. 2021), overriding any effects from container size or media composition.

The presence of healthy roots is a good indicator of plant performance after transplanting and is one of the most widely used tests of assessing seedling quality (Landis et al. 2010). In this study, examination of the root system of argan seedlings revealed the presence of both individual and multiple root deformations, most of which affected the morphology of the taproot. However, they do not appear to be related to the nursery treatments used, with little variation in the occurrence of root deformations between both container sizes and growing media. Nevertheless, they were still considerable, which presents a problem as they have been observed to hinder the growth of argan plants by negatively affecting water intake, thus leading to a dysfunction of the storage of carbohydrate reserves (Bellefontaine et al. 2013). Root deformations induced during nursery production also result in poor post-planting growth in the field linked to factors including poor physiological functioning as a result of shallow soil exploration (Falconnet et al. 1990). In semi-arid countries, the quality of the root and aerial systems of young plants is identified as the key factor in survival and juvenile growth problems. The root deformations of argan seedlings can also be detrimental to the mycorrhization of argan seedlings in the nursery and therefore affect the quality of seedlings (El Maati et al. 2015). Indeed, it has been shown that the mycorrhizal complex of argan seedlings grown in nurseries has a determining impact on the success of the plant and therefore on the effective establishment of argan plantations, even on poor soils (Nouaim & Chaussod 1997, 2002; Mrabet et al. 2014). In addition, Moroccan argan forests are generally located in degraded areas, which can lead to a weakness of the mycorrhizal potential of the soil (Benabid 2000; Kechairi 2009). Thus, the adoption of practices promoting the mutualistic association of argan seedlings with mycorrhizal fungi, particularly of the genus *Glomus*, by optimising the architecture of the root system should be imperative in the cultivation of seedlings in nurseries (Chakhchar et al. 2020).

The combined effect of large containers and acacia compost presents interesting nursery regimes that are recommended for the production of argan seedlings. However, it is important to note that the increase in the size of the containers can lead to an increase in production costs. Their use should be justified only when the performance of the seedlings benefits from the investment in additional resources. This is often the case in the production of seedlings for more difficult conditions such as semi-arid and arid Mediterranean regions characterised by limited available soil moisture. Indeed, there, large seedlings often outperform small seedlings (Andivia et al. 2021).

Conclusions

The study of the individual and joint effects of container size and growing medium on morphological traits and biomass of argan seedlings grown in nurseries revealed highly significant influences. The composition of growth substrate influenced the occurrence of root deformations and thus the overall quality of the seedlings. The 500 cm^3 containers yielded seedlings with attractive morphological traits (larger, clumpier seedlings with reduced root deformations) compared to the other two containers that were generally characterized by inferior seedlings. The growing medium composed entirely of acacia compost, as well as the media based on a mixture of Acacia compost and potting soil in equal proportions, favoured better seedling growth. Indeed, more robust seedlings, characterised by a higher biomass production were observed under these substrates, thus underlining the importance of these conditions for the production of good quality plants. They are, therefore, recommended for the nursery-production of this species for reforestation purposes. Although this study is intended to provide a better understanding of nursery-specific factors and conditions that influence seedling quality, more comprehensive studies should be undertaken. The focus here was on the nursery phase, and while the results are satisfactory, a broader scope involving monitoring of seedling performance in the field after transplanting would improve observations and provide an even richer source of data for forest planners and managers, helping to reverse the degrading trend of an important forest species in the fight against desertification.

Competing interests

The authors declare that they have no financial or non-financial competing interests.

Authors' contributions

YD participated in the conception and design of the study, including the implementation of the field experiment, and in the drafting of the manuscript. YD, AB, CAO, and MMOU participated in the data analysis. AS, MF, LK, FA and AEA contributed to the revision of the manuscript. All authors read and approved the final manuscript.

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Appendices

S 1- P54	S 6- P38	S 3- P28
S 4- P54	S 1- P28	S 3- P54
S 1- P38	S 7- P54	S 2- P28
S 2- P38	S 7- P28	S 6- P54
S 5- P28	S 3- P54	S 6- P28
S 7- P28	S 4- P38	S 7- P28
S 5- P28	S 4- P54	S 2- P38
S 3- P38	S 1- P28	S 7- P54
S 4- P28	S 7- P38	S 3- P38
S 3- P28	S 5- P38	S 5- P54
S 2- P28	S 7- P54	S 5- P28
S 1- P38	S 3- P28	S 2- P38
S 3- P54	S 2- P28	S 2- P54
S 7- P28	S 4- P28	S 1- P54
S 6- P38	S 4- P38	S 3- P38
S 2- P38	S 7- P54	S 4- P28
S 5- P38	S 6- P38	S 6- P28
S 5- P54	S 1- P54	S 2- P54
S 2- P28	S 6- P54	S 4- P38
S 1- P38	S 4- P54	S 7- P38
S 2- P54	S 5- P38	S 6- P28
S 4- P38	S 5- P54	S 6- P54
S 1- P28	S 7- P38	S 3- P28
S 1- P54	S 3- P38	S 3- P54
S 4- P54	S 5- P28	S 1- P28
S 5- P54	S 5- P38	S 1- P38
S 7- P38	S 6- P54	S 6- P28
S 6- P38	S 4- P28	S 2- P54

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FIGURE A1: Experimental layout showing the combinations of container size (P28, P38 and P54) and growing media substrate (S1 to S7).

FIGURE A2: Seed sowing into the container cells

FIGURE A3: Examples of the root deformations observed on seedlings