horticulturae

Article

Variation in Seed Traits, Germination Performance, and Seedling Morphology of *Cotinus coggygria* (Scop.) in Relation to Provenance and Seed Size

Askin Gokturk * and Asiye Surmeli

Department of Forest Engineering, Faculty of Forestry, Artvin Çoruh University, 08700 Artvin, Türkiye; asiyesr@gmail.com
* Correspondence: agokturk@artvin.edu.tr

Abstract

Cotinus coggygria (Scop) is a medicinally valuable species naturally distributed in the Artvin region of Turkiye. However, information on its seed traits, germination behavior, and seedling morphology in relation to seed size and provenance remains limited. This study aimed to evaluate the effects of seed size and provenance on the seed characteristics, germination, and seedling morphological traits of *C. coggygria*. Seeds were collected from four provenances (Seyitler, Tepekoy, Eskikale, and Tortum) and classified into large and small size groups using a 2 mm sieve. The seed traits of length, diameter, thickness, sphericity, volume, and thousand-seed weight were considered. To break seed dormancy, the seeds were subjected to sulfuric acid scarification and cold stratification treatments. Germination trials were conducted under nursery conditions using 45-cell trays in a randomized block design with four replicates. The mean germination time was significantly affected by provenance, whereas seed size and pretreatment combinations had no significant effects. Seed size did not significantly influence seedling morphology, whereas provenance caused significant differences. Seedlings originating from Eskikale exhibited greater height and root collar diameter, with root mass fractions ranging from 80.25% to 82.78%. These results indicate that provenance is a key factor influencing germination and seedling morphology rather than seed size.

Keywords: *Cotinus coggygria*; seed size; seed quality; germination; pretreatment; seedling morphology

1. Introduction

Smoke tree (*Cotinus coggygria*) is a medicinal and aromatic species mainly distributed in the Mediterranean region and East Asia and is widely recognized for its high ecological and ornamental value [1–3]. It has long been used in traditional medicine for wound healing, antidiarrheal purposes, and the treatment of various skin diseases, reflecting its considerable medicinal value [4]. Numerous scientific studies have characterized its medicinal and aromatic properties, particularly the essential oils found in its leaves and stems [5–8]. It is also a landscape plant that is used extensively in landscaping and afforestation [9].

Although several studies have addressed the removal of germination barriers [10–12] in the seeds of this species, no research has examined the influence of seed size, which is a key factor affecting germination and dormancy, or evaluated root and shoot biomass, which is critical for assessing the species' potential success in afforestation.

Academic Editor: Min Wei

Received: 9 February 2026
Revised: 20 March 2026
Accepted: 24 March 2026
Published: 1 April 2026

As a slow-growing, multi-stemmed shrub, *C. coggygria* typically reaches a height of 3–5 m and forms a scattered crown with a diameter of 3–4 m. This light-loving species tends to grow rapidly and produces oils in its leaves and shoots [6]. Its leaves turn red in autumn, making it an aesthetically pleasing addition to the urban landscape [9]. Its showy inflorescences, colorful leaves, and decorative fruits make it a valuable ornamental plant for landscaping.

C. coggygria is resistant to drought, cold, and frost but sensitive to humidity. It can grow successfully in hot, sunny, and rocky areas. This plant, notable for its strong root system and high sprouting ability, has golden-yellow wood and has traditionally been used in leather dyeing [9]. With its medicinal properties, it is used in folk medicine for anti-inflammatory, antimicrobial, and wound-healing purposes, and scientific studies have shown that it has antioxidant and anticancer effects [13,14]. However, it has been reported to be toxic because of its high gallotannin content (over 25%) [15].

Its natural distribution in drought-affected inland areas, along road slopes, and on sloped, erosion-prone areas suggests that this species has potential for use in afforestation and erosion control. It is recommended that species with natural distributions be used as seedling material in erosion-prone areas [16]. In this context, the use of local seed provenances is particularly emphasized in restoration and habitat creation efforts, as they are generally considered better adapted to local environmental conditions [17].

Seed provenance is a primary determinant of successful afforestation. The genetic provenance, quality, and physiological characteristics of seeds, which are the primary starting materials for afforestation efforts, directly affect success [18]. Using high-quality seeds of appropriate provenance is critical for preventing losses in time, labor, and economic resources during seedling production.

Seed size directly affects many parameters, such as germination percentage [19], mean germination time [20], and seedling growth vigor [21,22]. Large seeds generally yield more favorable results in terms of germination success and seedling quality and provide an advantage in the transmission of genetic characteristics [23]. Germination performance tends to be higher in large seeds than in small seeds, and large seeds are more effective at producing vigorous seedlings [24,25]. Seedling quality is an important factor that influences the success of forest plantations [26].

Although seedling quality is determined by morphological and physiological characteristics, in practice, morphological criteria such as the root collar diameter, height, and fresh-dry weights of roots and shoots are generally considered [27]. Therefore, to produce high-quality seedlings, it is necessary to understand the germination biology of the species and its seed physiological requirements.

This study aimed to investigate the effects of provenance and seed size on the morphological characteristics of *C. coggygria* seedlings, and to determine the changes in the morphological characteristics and germination behaviors of seeds from different provenances to enable seed size assessment.

2. Materials and Methods

2.1. Provenances and Study Site

The seeds used in this study originated from the villages of Seyitler in Artvin Province; Tepekoy; Eskikale in Savsat District; and Tortum in Erzurum Province, Turkiye (Figure 1; Table 1). The seeds' morphological traits were measured at the Afforestation and Seed Laboratory. Pretreatments were then applied to the seeds to evaluate their germination performance. The seeds were sown under nursery conditions at the Forestry Application and Research Center of Artvin Çoruh University, located in Seyitler (Artvin, Türkiye), where seedlings were grown. After the growing period, the seedlings were removed from the nursery beds and transported to the Afforestation and Seed Laboratory, where their morphological traits were measured again.

Figure 1. Areas where seeds were collected.

Table 1. Map of the provenances where *C. coggygria* seeds were collected.

Provenance		Coordinate (Latitude/Longitude)	Elevation	Aspect
1	Eskikale	41.272577/42.262403	730	South
2	Seyitler	41.19920/41.85332	540	South
3	Tepekoy	41.267998/42.297400°	930	Southwest
4	Tortum	40.480319/41.504492	1195	South

The climatic conditions of the study area and seed collection provenances were characterized using long-term meteorological data. Climate data were obtained from the nearest meteorological station, and long-term averages based on approximately 50 years of observations were used to represent the regional climate. The study nursery, where seed germination and seedling production were carried out, is located in the Seyitler provenance.

To provide a broader ecological context, climatic data were also estimated for the other seed collection provenances (Tortum, Tepekoy, and Eskikale). The climatic values for these provenances were derived by the spatial interpolation of the meteorological station data according to their geographic locations and elevations. Monthly mean temperature and monthly precipitation values were used to describe seasonal climatic patterns, while mean annual temperature and total annual precipitation were calculated to characterize the overall climatic conditions of the provenances (Figure 2).

2.2. Seed Material

C. coggygria seeds are found in wig-like bunches. For this study, seeds were collected from the trees in bunches and mechanically separated. Seeds were collected in June 2018. Before storing the seeds, empty seeds were removed by floating them on water. The seeds were then dried at room temperature for 10 days and stored in a refrigerator at 5 °C in sealed plastic bags. Because the seeds were collected in June 2018 but not sown immediately, they were kept under storage conditions until the pretreatments were applied. In order to ensure that the 60-day stratification period would end exactly at the planned sowing time in March 2019, the pretreatment procedures were initiated in January 2019. Accordingly, all seeds—including those later assigned to the control group and those subjected to sulfuric acid scarification—were stored under identical conditions (5 °C in a refrigerator) from the time of collection in June 2018 until the initiation of pretreatments in January 2019.

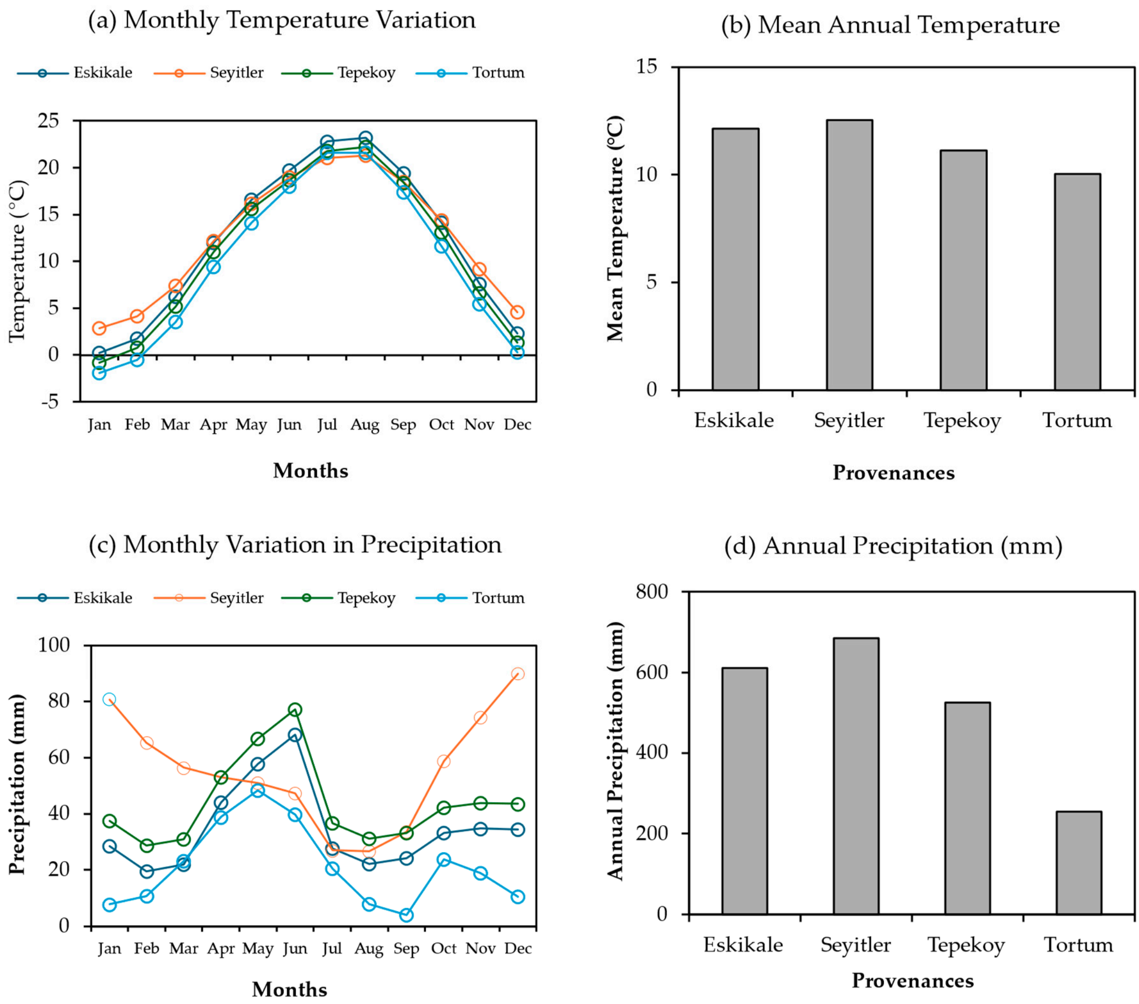

Figure 2. Temperature and precipitation characteristics of the provenances: (**a**) monthly temperature variation, (**b**) mean annual temperature, (**c**) monthly precipitation variation, and (**d**) total annual precipitation for Tortum, Tepekoy, Eskikale, and Seyitler.

2.3. Seed Size Classification

A 2 mm mesh sieve was used to classify the seeds according to size. Seeds that passed through the sieve were classified as small seeds, and those that remained on the sieve were classified as large. All morphological measurements of the seeds were performed on the overall sample prior to size grouping and repeated separately for both small and large seed groups.

2.4. Seed Traits

In this study, the morphological characteristics of seeds, including length, width, thickness, thousand-seed weight, and filling ratio, were determined. To evaluate the average seed size, a randomly selected sample of 100 seeds was used, and the three principal perpendicular dimensions—length (L, mm), width (W, mm), and thickness (T, mm)—were measured for each seed. All measurements were conducted using a digital caliper with millimeter (mm) precision. Based on these dimensional data, the arithmetic mean diameter (Da, mm), geometric mean diameter (Dg, mm), and sphericity (Sp, %) of the seeds were calculated using Formulas (1)–(3) as described by Mohsenin [28], and the seed volume (V, mm^3) was calculated using Formula (4) as described by Jain and Bal [29].

$$D_a = (L + W + T)/3 \tag{1}$$

$$D_g = (LWT)^{1/3} \tag{2}$$

$$S_p = (LWT)^{1/3}/L \tag{3}$$

$$V = 0.25\left[\left(\frac{\pi}{6}\right)L(W+T)^2\right] \tag{4}$$

The thousand-seed weight (*TSW*) was measured using a precision scale on eight randomly selected samples of 100 seeds each, and determined using the average weight calculation method based on the obtained data [30].

The seed fill rate was determined by using three separate samples selected from the previously weighed samples. In this process, seeds were cut crosswise, their internal filling was visually assessed, and the percentage of filled seeds was calculated.

Seed weight and filling rate measurements were conducted in two stages: before and after flotation. These measurements were repeated for each group after the seeds were grouped according to size.

2.5. Pretreatments

This study aimed to determine the effects of seed provenance and size on germination, rather than developing new methods to overcome germination inhibition in *C. coggygria* seeds. Therefore, pretreatment methods previously proven to be effective in the literature were selected. Commonly recommended methods for overcoming germination inhibition in *C. coggygria* seeds include cold stratification and chemical scarification with sulfuric acid (H_2SO_4) (Merck, Darmstadt, Germany). In this study, appropriate cold stratification times were determined to be 30 and 60 days, and appropriate chemical scarification times with sulfuric acid were determined to be 20 and 40 min. Sulfuric acid was used at a concentration of 95% in the chemical scarification process, and 15 mL of H_2SO_4 was applied to each seed group.

The pretreatment combinations used in this study were arranged in four different combinations: chemical scarification times in sulfuric acid (20 and 40 min) and cold stratification times (30 and 60 d). Untreated control groups were also included in this study. Thus, five different pretreatments were evaluated for each provenance and seed size group.

In the combination of pretreatments, seeds were first chemically scarified with sulfuric acid, followed by cold stratification. Seeds to be stratified were first moistened, placed in cheesecloth bags, and stored in glass jars between two layers of moist sand in a refrigerator at 5 °C. Throughout the stratification process, regular weekly checks were performed to ensure that the environmental conditions were maintained and that the medium did not dry out.

2.6. Experimental Design and Seedling Production

Sowing was performed in March 2019 in 45-cell trays placed in seedbeds established in the nursery, under open-field conditions. A randomized block design with four replicates was used. Only one seed was sown in each cell of the 45-cell trays, and a total of 180 seeds (4 × 45 cells) were sown for each pretreatment combination. A homogeneous growth medium, obtained by mixing peat and perlite in a 3:1 ratio, was used as the sowing medium for all treatments. Following the initiation of germination, germination controls were performed regularly at weekly intervals, and newly germinated individuals were counted and recorded.

During the germination period, irrigation was applied daily until germination was completed. After germination, the irrigation frequency was reduced to twice per week and continued at this frequency until the end of the growing season.

2.7. Germination Percentage and Mean Germination Time

Weekly checks were performed from the date of sowing, and germination numbers were recorded starting 9 April 2019, when the germination began. The final germination was observed on 28 May 2019. Formula (5) was used to determine *GP* [31], where n is the number of seeds that were germinated and N is the total number of sown seeds. Formula (6) was used to calculate the mean germination time (*MGT*) [32], where n1. . .n is the number of seeds germinated on the nth day, t1. . .n is the number of days from the start of the germination test until the germination control is performed, and T is the total number of germinated seeds.

$$GP = \sum n/N \times 100 \tag{5}$$

$$MGT = \frac{(n1 \times t1) + (n2 \times t2) + (n3 \times t3) + \ldots + (ni \times ti)}{T} \tag{6}$$

2.8. Morphological Characteristics of Seedlings

In this study, the morphological characteristics of the seedlings were assessed, including the seedling height (*SH*), root collar diameter (*RCD*), dry root weight (*DRW*), dry stem weight (*DSW*), and seedling dry weight (*SDW*). At the end of the growing season, on 11 December 2019, the seedlings were carefully removed from the trays. To eliminate the possible effects of pretreatment applications on morphological traits, only seedlings propagating from seeds that received the same pretreatment were used in the evaluation process. Morphological measurements were conducted on 240 seedlings, representing four provenances and two seed size classes, with 30 seedlings sampled for each provenance–seed size combination.

Prior to measurement, the roots of the uprooted seedlings were gently washed to remove adhering soil, and the leaves were removed from the stems. Seedling heights were measured using a ruler with millimeter (mm) precision, and root collar diameters were measured using a digital caliper with millimeter (mm) precision. Subsequently, the seedlings were severed at the root collar, and the root and stem sections were separated. The fresh weights of the root and stem sections were measured using a digital scale with a precision of 0.001 g. The samples were then placed in paper envelopes and dried in an oven at 105 °C for 24 h. After completion of the drying process, the dry weights were determined by reweighing the samples using the same digital balance.

2.9. Root Mass Fraction, Shoot/Root Ratio, and Sturdiness Index

The root mass fraction (*RMF*), shoot/root ratio (*S*:*R*), and sturdiness index (*SI*) are morphological quality measures commonly used to determine seedling quality [33]. In this study, these quality indicators were not used to classify *C. coggygria* seedlings as high- or low-quality but rather to comparatively assess their developmental levels. The primary rationale for this assessment approach was the observation that root development in *C. coggygria* seedlings was more advanced than stem development at the time of the measurement (Figure 3).

In the present study, Formulas (7) and (8) were used to calculate the root mass fraction (*RMF*), shoot/root ratio (*S*:*R*), and sturdiness index (*SI*). The root mass fraction expresses the ratio of root dry weight (*RDW*) to the total dry weight of the seedling (*TDW*) and is calculated as a percentage [34]. The shoot/root ratio (*S*:*R*) represents the proportion of stem (shoot) dry weight (*SDW*) to root dry weight and is widely used as an indicator of postplanting performance and to evaluate the drought-avoidance potential of seedlings [35]. The sturdiness index is the ratio of seedling height (*SH*, cm) to root collar diameter (*RCD*, mm) and is an indicator that evaluates the vertical growth of seedlings according to diameter development [36]. In this study, seedling height values are expressed in millimeters (mm) when calculating the sturdiness index. The sturdiness index reflects the strength and stability capacity of seedlings [37] and is used to categorize seedlings by quality: SI values ≤ 50 indicate first-class seedlings, values between >50 and $\leq$60 indicate second-class seedlings, and values > 60 classify seedlings as cull seedlings [27].

$$RMF = \frac{DRW}{TDW} \times 100 \tag{7}$$

$$S:R = \frac{SDW}{RDW} \tag{8}$$

$$SI = \frac{SH}{RCD} \tag{9}$$

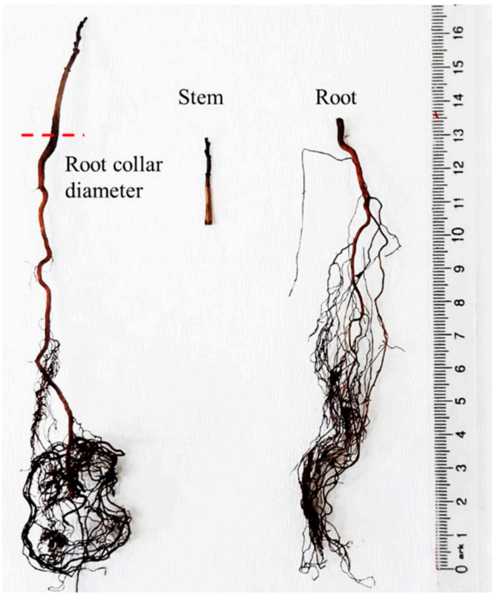

Figure 3. One-year-old *C. coggygria* root and stem samples of the seedlings.

2.10. Statistical Analysis

Statistical analyses were conducted using the SPSS 19.0 statistical software package (IBM Corp., Armonk, NY, USA). Prior to the analysis, the normality of the data was examined. All variables met the assumption of normality except germination percentage (*GP*) and mean germination time (*MGT*); therefore, an arcsine transformation was applied to these variables before statistical analyses. Seed traits were calculated for each provenance across large, small, and combined seed groups. However, analyses of provenance-related differences were performed using the combined seed groups without separating seeds by size. The large and small seed groups were defined for descriptive purposes only, and no statistical comparisons among provenances were conducted within these groups. Germination parameters, including germination percentage and mean germination time, were analyzed with respect to provenance, seed size, and pretreatment.

Germination percentage and mean germination time values were derived from a multifactorial statistical analysis performed using SPSS 19.0 within a general linear model framework, in which provenance, seed size, pretreatment, and their interaction terms were evaluated simultaneously. Accordingly, the reported values correspond to the estimated marginal means obtained from the full model. Depending on the main factor considered, the data were pooled across the remaining factors. For provenance-based comparisons, germination percentage and mean germination time values were calculated using the combined dataset across all pretreatment applications and seed size groups, whereas for pretreatment-based comparisons, the values were calculated using the combined dataset across all provenances and seed size groups.

The morphological characteristics of the seedlings were evaluated considering provenance and seed size factors. Multivariate analysis of variance was used to determine the effects of these factors on the measured parameters. When statistically significant differences were detected, the Duncan multiple range test was applied to identify differences among the groups.

3. Results

3.1. Variation in Seed Traits

Analysis of variance showed that both provenance and seed size had significant effects on seed length (*L*), width (*W*), thickness (*T*), and seed volume (*V*) ($p < 0.01$). Although the interaction between provenance and seed size was not significant for seed width and length ($p > 0.05$), it was significant for seed thickness and volume ($p < 0.01$) (Table S1).

Eskikale showed the highest mean values for seed length (4.758 mm), thickness (1.670 mm), and volume (16.526 mm^3), whereas Seyitler demonstrated the highest mean seed width (3.410 mm) (Table 2). Seed size differences between groups were expected due to size separation. The statistically significant differences observed among the seed groups indicate that the seeds were validly classified into large and small seed groups. In the large seed group, seed length ranged from 4.659 to 5.009 mm, the seed width ranged from 3.298 to 3.572 mm, seed thickness ranged from 1.564 to 1.779 mm, and seed volume ranged from 14.518 to 19.004 mm^3. In the small seed group, the seed width varied from 3.009 to 3.302 mm, seed length from 4.326 to 4.659 mm, seed thickness from 1.427 to 1.608 mm, and seed volume from 11.205 to 14.167 mm^3 (Figure 4).

Table 2. Variation in seed length (mm), width (mm), thickness (mm), and volume (mm^3) among provenances.

Provenance	*L*	*W*	*T*	*V*
Eskikale	4.758 ± 0.499 ^{ab*}	3.437 ± 0.325 ^{a}	1.670 ± 0.179 ^{a}	16.526 ± 4.205 ^{a}
Seyitler	4.820 ± 0.437 ^{a}	3.410 ± 0.292 ^{a}	1.566 ± 0.140 ^{c}	15.765 ± 3.050 ^{b}
Tepekoy	4.706 ± 0.457 ^{b}	3.325 ± 0.330 ^{b}	1.620 ± 0.105 ^{b}	15.238 ± 3.365 ^{b}
Tortum	4.493 ± 0.479 ^{c}	3.153 ± 0.325 ^{c}	1.495 ± 0.157 ^{d}	12.862 ± 2.926 ^{c}

* Different letters within the same column indicate statistically significant differences according to Duncan's multiple range test ($p < 0.01$).

The analysis of variance indicated that provenance and seed size had statistically significant effects on the arithmetic mean diameter (*Da*), geometric mean diameter (*Dg*), sphericity (*Sp*), and thousand-seed weight (*TSW*) ($p < 0.01$). In addition, the provenance $\times$ seed size interaction was significant for Da and Dg, whereas its effect on *Sp* was not statistically significant ($p > 0.05$) (Table S2).

Statistically significant differences among provenances were detected for *Da*, *Dg*, *Sp*, and *TSW* ($p < 0.05$), with the Eskikale provenance exhibiting the highest mean values for all parameters (Table 3). In the large-seed group, the *Da* values ranged from 3.174 to 3.453 mm, and the *Dg* values ranged from 2.881 to 3.163 mm, whereas the *Sp* and *TSW* values varied between 0.614 and 0.634, and 9.687 and 11.840 g, respectively. In the small seed group, the *Da* values ranged from 2.921 to 3.156 mm, *Dg* values from 2.638 to 2.857 mm, Sp values from 0.615 to 0.634, and TSW values from 7.399 to 8.961 g (Figure 5).

https://doi.org/10.3390/horticulturae12040426

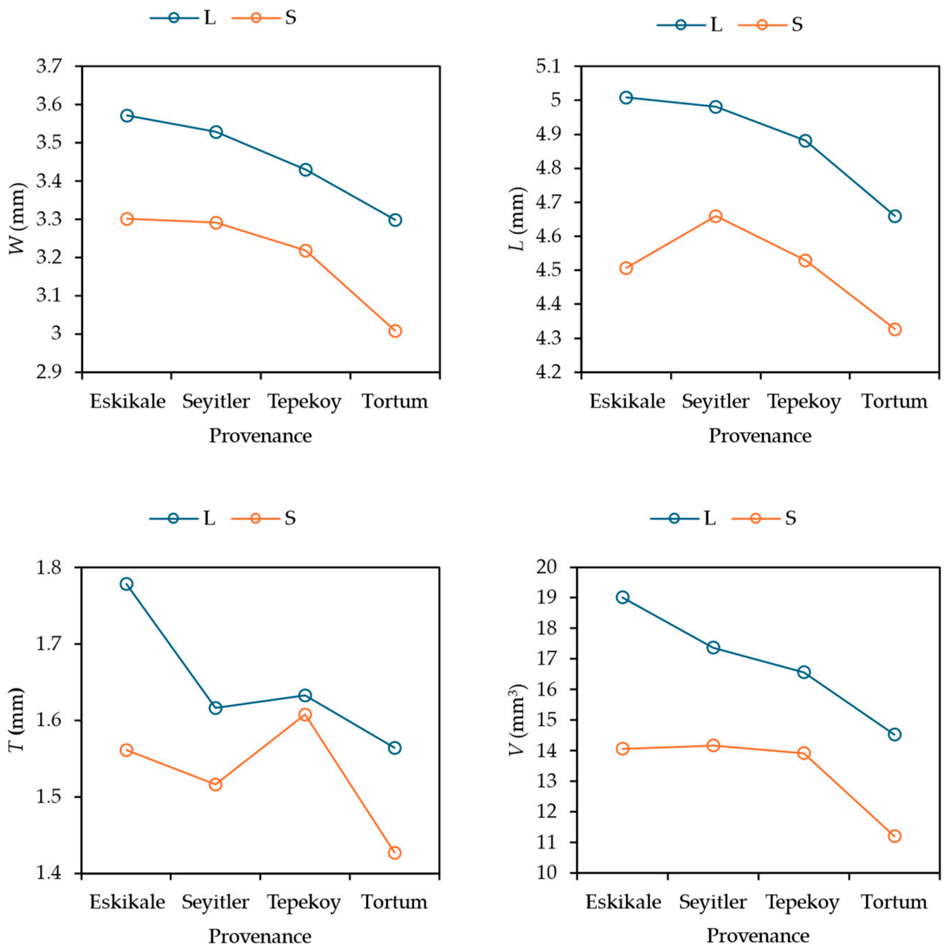

Figure 4. Seed width, length, thickness, and volume according to provenances and seed size classes.

Table 3. Variation in seed diameter (mm), sphericity (%), and 1000-seed weight (g) among provenances.

Provenance	*Dg*	*Da*	*Sp*	*TSW*
Eskikale	3.006 ± 0.251 ^{a*}	3.288 ± 0.278 ^{a}	0.634 ± 0.037 ^{a}	10.401 ± 1.497 ^{a}
Seyitler	2.947 ± 0.190 ^{b}	3.266 ± 0.216 ^{a}	0.614 ± 0.041 ^{c}	9.981 ± 0.953 ^{b}
Tepekoy	2.932 ± 0.192 ^{b}	3.217 ± 0.235 ^{b}	0.626 ± 0.040 ^{ab}	9.803 ± 1.077 ^{c}
Tortum	2.760 ± 0.208 ^{c}	3.047 ± 0.236 ^{c}	0.618^{b} ± 0.052 ^{c}	8.467 ± 1.197 ^{d}

* Different letters within the same column indicate statistically significant differences according to Duncan's multiple range test ($p < 0.05$).

In evaluating the germination potential of *C. coggygria* seeds, analyses of the seed fill rates before and after flotation revealed that the percentage of empty seeds could reach up to 60%. Measurements after the flotation method revealed a significant removal of empty seeds, demonstrating that this can be used as an effective physical separation method for *C. coggygria* seeds (Figure 6).

3.2. Variation in Germination Performance

The results show that both provenance and pretreatment had significant effects on the germination percentage ($p < 0.05$), while these factors did not significantly influence the mean germination time. However, seed size did not significantly affect either the germination percentage or mean germination time ($p > 0.05$).

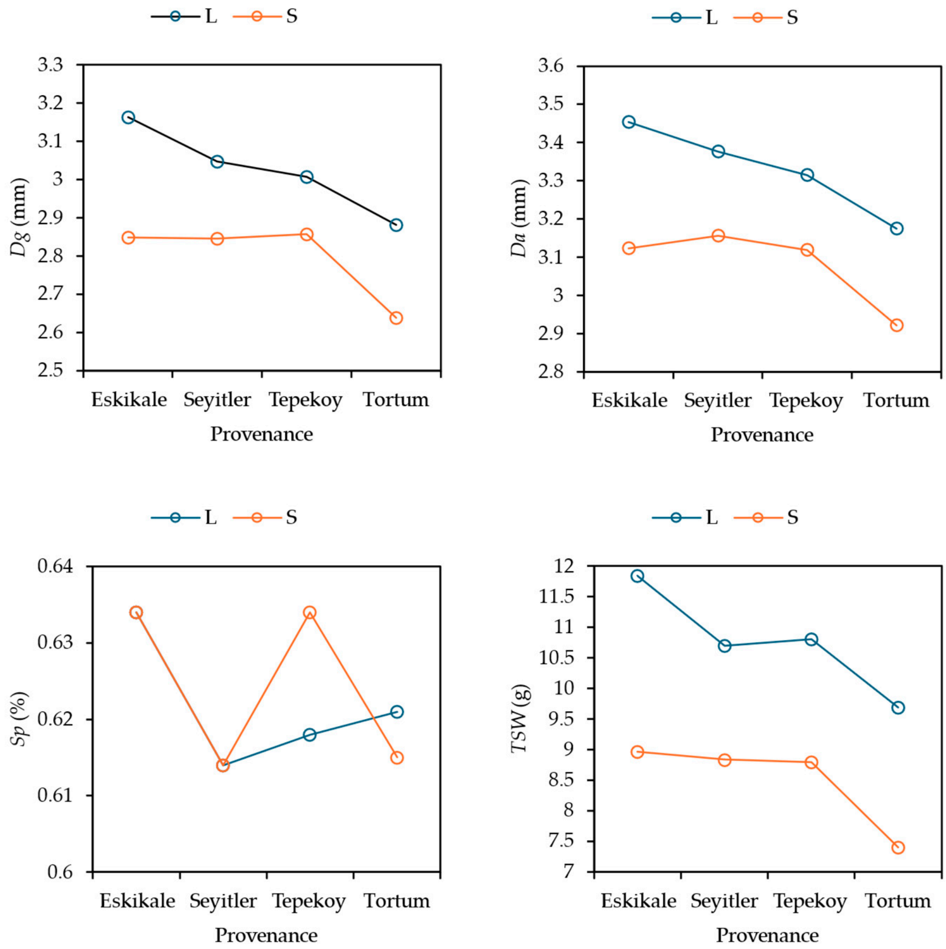

Figure 5. Seed diameter (mm), sphericity (mm), and 1000-seed weight (g) among provenances and seed size classes.

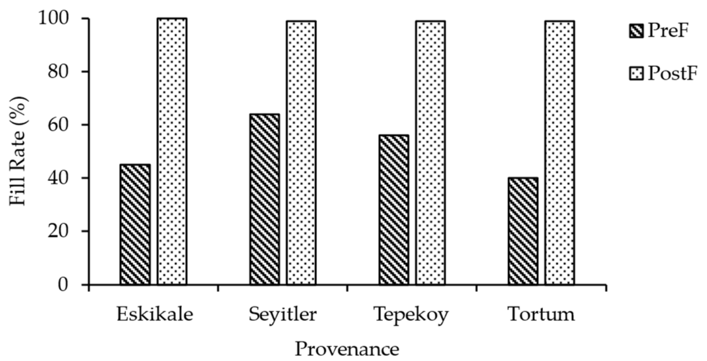

Figure 6. Seed fill rates according to provenance (PreF: Pre-Flotation; PostF: Post-Flotation).

When the interactions between the factors were evaluated, it was determined that the provenance × pretreatment interaction had significant effects on both the germination percentage and mean germination time ($p < 0.05$), the provenance × seed size interaction affected only the mean germination time, and the provenance × pretreatment × seed size triple interaction had a significant effect only on the mean germination time (Table S3).

The highest germination percentages (52.01% and 52.83%) were observed in seeds originating from the Eskikale and Seyitler provenances. The mean germination time varied between 20.94 and 24.40 days according to provenance group (Table 4).

Table 4. Duncan test results showing differences in germination percentage and mean germination time among provenances (values based on pooled data across all pretreatments and seed size groups).

Provenance	Germination Percentage	Mean Germination Time
Eskikale	52.01 ± 36.97 [a*]	20.98 ± 9.17
Seyitler	52.83 ± 11.36 [a]	21.41 ± 10.38
Tepekoy	41.92 ± 25.76 [b]	24.40 ± 7.89
Tortum	39.99 ± 25.74 [b]	23.10 ± 9.42

* Different letters within the same column indicate statistically significant differences according to Duncan's multiple range test ($p < 0.05$).

Pretreatments resulted in higher germination percentages compared with the control treatment (Table 5). However, despite these higher values, no statistically significant differences were detected among the pretreatment types for germination percentage ($p > 0.05$). In contrast, the control treatment formed a separate statistical group with significantly lower germination percentage values ($p < 0.05$). The mean germination time varied slightly among the pretreatments, but these differences were not statistically significant ($p > 0.05$).

Table 5. Duncan test results showing differences in germination percentage and mean germination time among pretreatments (values based on pooled data across all provenances and seed size groups).

Pretreatment	Germination Percentage	Mean Germination Time
20 min H_2SO_4 + 30 d CS *	58.76 ± 19.80 [a**]	21.34 ± 2.23
20 min H_2SO_4 + 60 d CS	53.88 ± 23.24 [a]	22.04 ± 2.35
40 min H_2SO_4 + 30 d CS	58.78 ± 18.77 [a]	22.13 ± 1.87
40 min H_2SO_4 + 60 d CS	58.00 ± 35.07 [a]	21.98 ± 3.38
Control	4.01 ± 4.20 [b]	24.86 ± 20.20

* CS: Cold stratification. ** Different letters within the same column indicate statistically significant differences according to Duncan's multiple range test ($p < 0.05$).

The provenance × pretreatment interaction revealed significant differences in both germination percentage and mean germination time, indicating that the effectiveness of the pretreatments varied among provenances. The optimal combination in this study was generally 40 min of H_2SO_4 scarification followed by 60 days of cold stratification (Figure 7). However, a 30-day stratification period produced better outcomes in the Tepekoy and Tortum provenances.

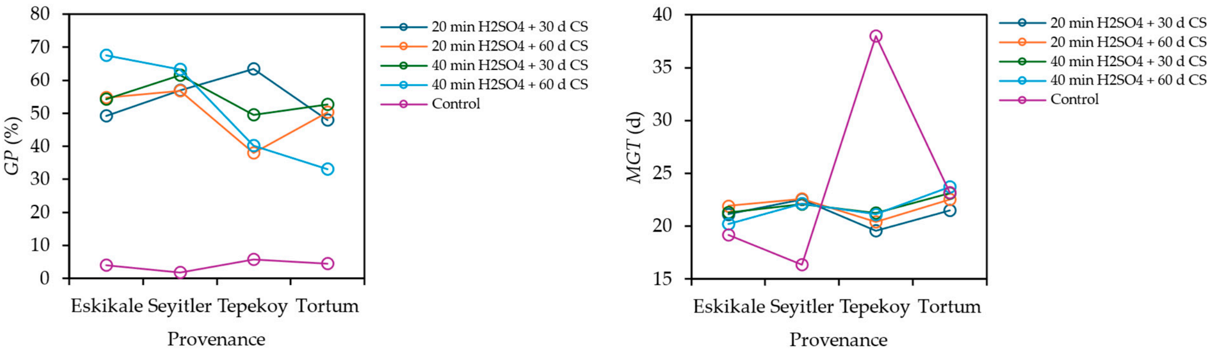

Figure 7. Germination percentage and mean germination time among provenances and pretreatments (values based on pretreatment comparisons within each provenance, independent of seed size).

Small seeds from the Eskikale provenance exhibited slightly higher germination percentages than large seeds (48.9% and 43.0%), whereas seeds from Tepekoy and Seyitler showed relatively balanced germination responses between seed sizes. In Tortum, large seeds germinated at a slightly higher rate than small seeds (39.1% vs. 36.3%, respectively). The mean germination time also varied inconsistently across provenances; in some cases (e.g., Seyitler), small seeds germinated more rapidly, whereas in others (e.g., Tortum), they germinated more slowly (Figure 8).

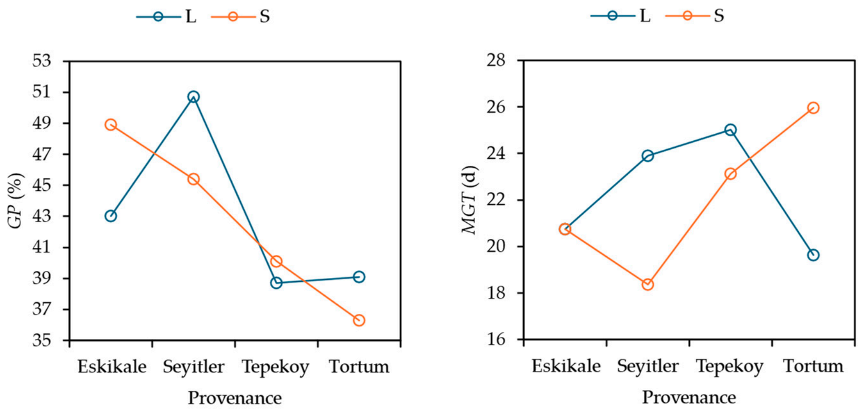

Figure 8. Germination percentage and mean germination time according to provenance and seed size groups based on pooled data from all pretreatments (values presented for seed size groups within each provenance, based on pooled data across all pretreatments).

The germination percentages increased in all provenances following pretreatment, with the highest values generally observed under 40 min H_2SO_4 + 60 days cold stratification, although Tepekoy and Tortum responded better to 30-day stratification. The seed size effects were not consistent across provenances; in some cases, small seeds germinated slightly better, while in others, large seeds showed higher germination, and the mean germination time varied irregularly between the seed size groups (Figure 9).

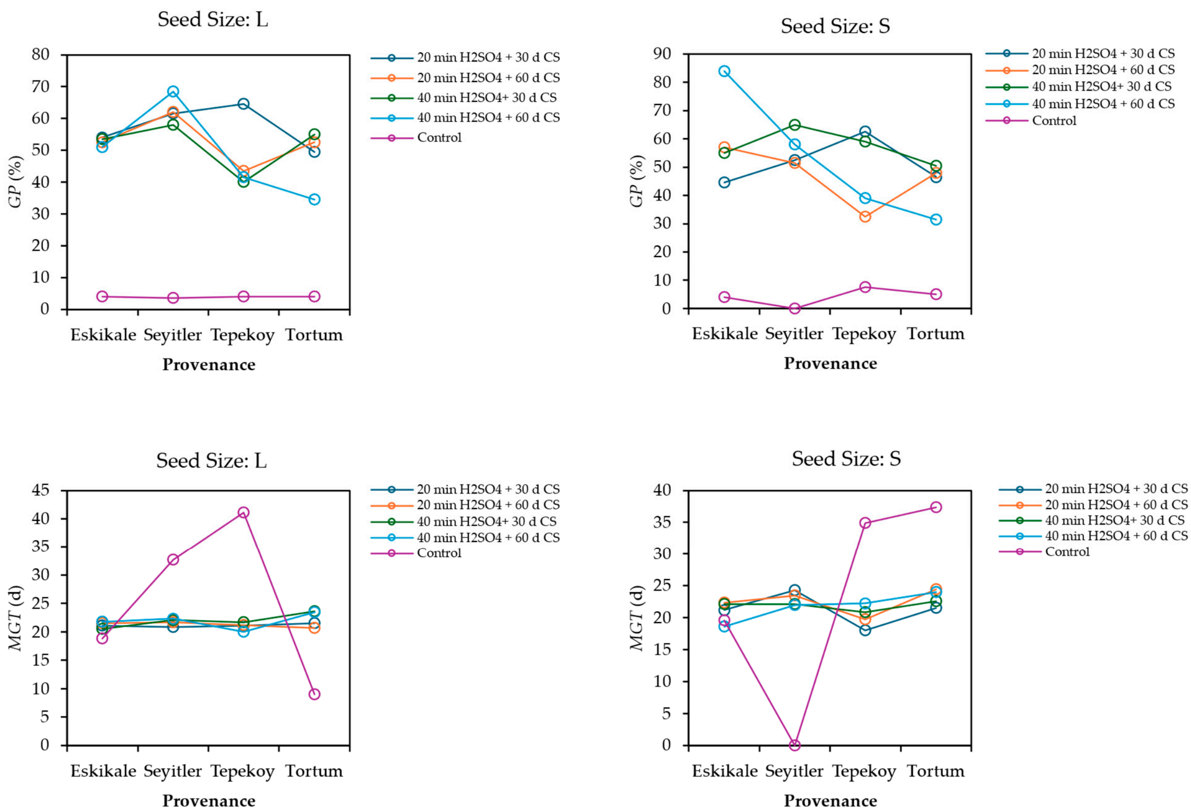

Figure 9. Germination percentages and mean germination times of seeds according to pretreatments, provenances, and seed size groups.

3.3. Variation in Seedling Morphology

The variance analysis conducted to determine the effects of provenance and seed size on the morphological characteristics and quality of seedlings revealed that the provenance factor had a statistically significant effect on seedling height and root collar diameter, while the seed size factor had significant effects on root and seedling dry weights (Table S4).

According to the results of this study, seedlings grown from seeds originating from Eskikale and Seyitler exhibited the greatest seedling height, while those originating from Eskikale, Seyitler, and Tepekoy showed statistically significantly higher root collar diameter values (Table 6).

Table 6. Duncan test results showing differences between provenances according to morphological characteristics of seedlings.

Provenance	Seedling Height (mm)	Root Collar Diameter (mm)	Dry Root Weight (g)	Dry Stem Weight (g)	Seedling Dry Weight (g)
Eskikale	60.12 ± 35.72 ^{a*}	2.71 ± 1.05 ^{a}	0.58 ± 0.48	0.14 ± 0.16	0.73 ± 0.64
Tepekoy	39.61 ± 18.87 ^{b}	2.63 ± 0.90 ^{a}	0.50 ± 0.52	0.12 ± 0.15	0.61 ± 0.63
Seyitler	58.76 ± 30.27 ^{a}	2.56 ± 0.84 ^{a}	0.53 ± 0.50	0.13 ± 0.15	0.66 ± 0.63
Tortum	49.25 ± 29.25 ^{ab}	2.15 ± 0.73 ^{b}	0.38 ± 0.37	0.09 ± 0.11	0.47 ± 0.48

* Different letters within the same column indicate statistically significant differences according to Duncan's multiple range test ($p < 0.05$).

Assessments according to provenance and seed size groups revealed that the morphological characteristics of the seedlings varied depending on both provenance and seed size. Seedlings obtained from small seeds tended to show higher values for most morphological characteristics compared with those obtained from large seeds (Figure 10). However, this trend was reversed in the Tortum provenance.

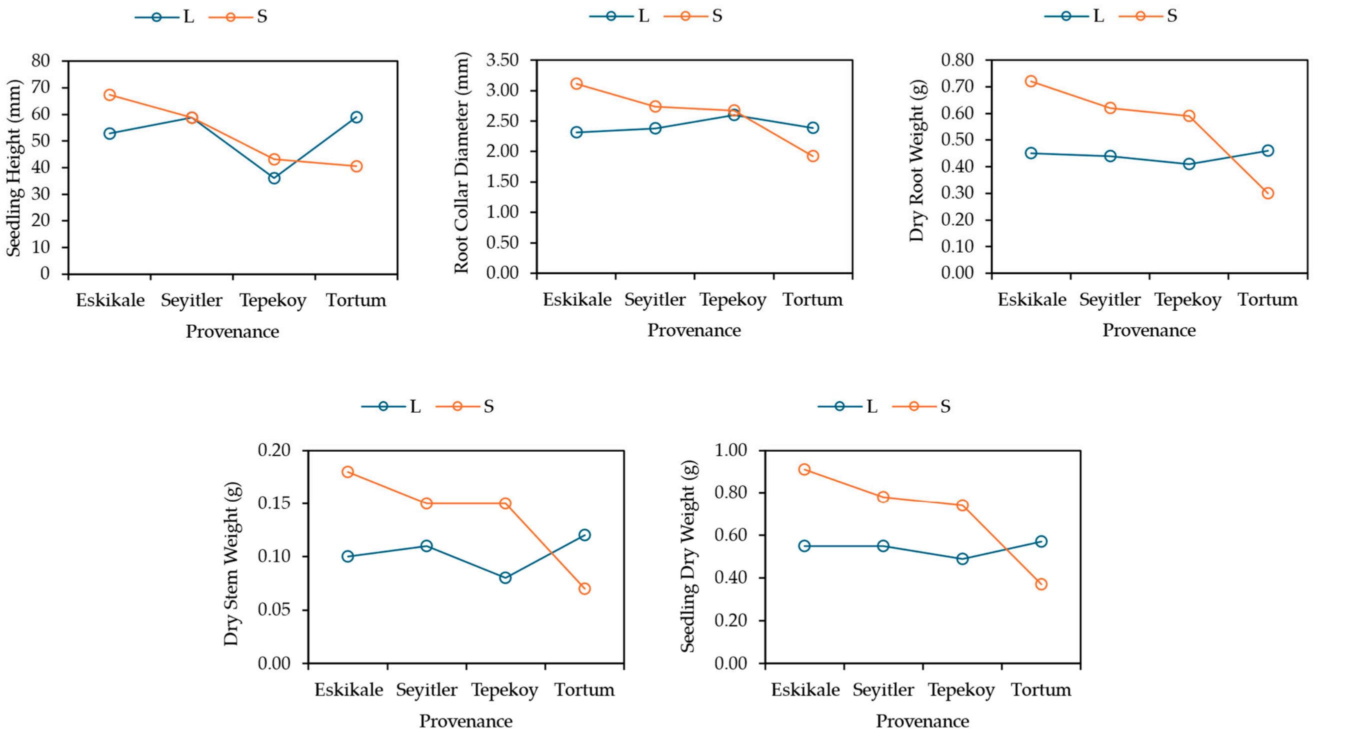

Figure 10. Morphological characteristics of seedlings according to provenances and seed size groups.

3.4. Variation in Root Mass Fraction, Shoot/Root Ratio, and Sturdiness Index

The analysis of variance revealed that the differences between the root mass fractions were not significant. The effects of provenance, seed size, and the provenance × seed size interaction on the root mass fraction were not statistically significant. Similarly, no significant differences in the shoot/root ratio values were observed (Table S5).

The root mass fraction values by provenance were 81.69% in Eskikale, 81.26% in Tepekoy, 80.25% in Seyitler, and 82.78% in Tortum. The shoot-to-root ratio varied between 0.22 and 0.31 among the provenances. The sturdiness index (*SI*) values were 21.53, 15.13, 22.94, and 22.04. Different letters indicate statistically significant differences among the treatments (Table 7).

Table 7. Duncan test results showing differences between provenances according to root mass fractions, shoot/root ratio, and sturdiness index of seedlings.

Provenance	RMF	S:R	SI
Eskikale	81.69 ± 4.24	0.23 ± 0.06	21.53 ± 7.11 [a*]
Tepekoy	81.26 ± 9.91	0.31 ± 0.68	15.13 ± 4.35 [b]
Seyitler	80.25 ± 6.12	0.25 ± 0.10	22.94 ± 7.76 [a]
Tortum	82.78 ± 7.43	0.22 ± 0.15	22.04 ± 7.32 [a]

* Different letters within the same column indicate statistically significant differences according to Duncan's multiple range test ($p < 0.05$).

When the root mass fraction values for all the provenances were compared by seed size, they were 81.30% for large seeds and 81.64% for small seeds. The highest root mass fraction was observed in seedlings derived from the small seeds of the Tortum provenance (83.46%) (Figure 11).

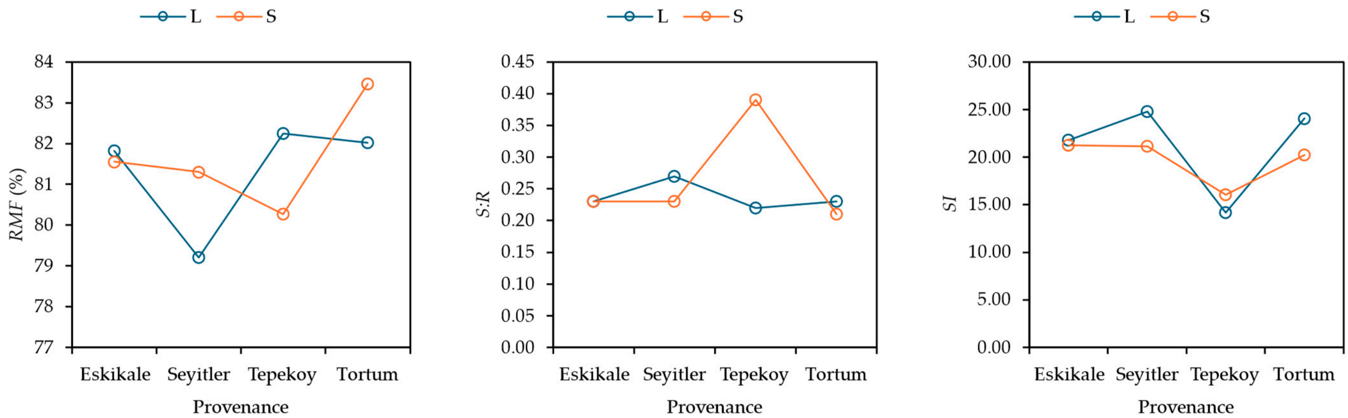

Figure 11. Root mass fractions, shoot/root ratio, and sturdiness index according to provenance and seed size group.

Although the provenance factor had a statistically significant effect on the sturdiness index of seedlings, the effects of seed size and provenance × seed size interaction were not significant. The sturdiness index in seedlings obtained from seeds of the Eskikale provenance was determined to be 21.80 for large seeds and 21.25 for small seeds. In seedlings obtained from the Tepekoy provenance, these values were 14.19 and 16.07 h for large and small seeds, respectively. In seedlings from the Seyitler provenance, the sturdiness index was 24.76 for large seeds and 21.13 for small seeds. In seedlings from the Tortum provenance, the sturdiness index was determined to be 24.06 for large seeds and 20.22 for small ones.

4. Discussion

4.1. Variation in Seed Traits in Relation to Provenance and Seed Size

The significant differences in seed length, width, thickness, and 1000-seed weight among *C. coggygria* seed provenances suggest that provenance factors influence seed traits in this species. Morphological variations among seeds of the same species sourced from different altitudes and geographical provenances have been documented in several studies [24,38–41]. Provenance-related variation in seed morphological characteristics is often associated with genetic differences and environmental conditions at the seed source [42].

Previous studies have shown that seed morphometric traits may vary considerably among populations of the same species, reflecting both genetic adaptation and maternal environmental effects. Such variations in seed size and weight are considered important indicators for the selection of suitable seed sources in afforestation and restoration programs [43].

In addition, environmental conditions experienced by mother plants can influence seed development and consequently affect seed traits such as size and mass. These maternal effects may contribute to differences in seed quality and subsequent seedling performance among provenances [44].

The climatic conditions of the seed source locations may also contribute to the observed variation in seed morphometric traits and germination performance. The climatic data of the sampling sites revealed noticeable differences in both temperature and precipitation regimes among the provenances. Seyitler, which represents the lowest elevation among the study sites, receives the highest annual precipitation, whereas Tortum, characterized by the highest elevation, exhibits comparatively lower precipitation and temperature values. Eskikale, located at an intermediate elevation approximately 200 m higher than Seyitler, receives the second-highest precipitation and, together with Seyitler, shows higher mean annual temperatures. These differences in moisture availability and thermal conditions may influence resource allocation during seed development and the accumulation of assimilates in developing seeds, ultimately affecting seed size, weight, and germination performance. Previous studies have also demonstrated that environmental conditions during seed development, particularly temperature and water availability, can significantly influence seed characteristics and subsequent germination behavior [42–45]. Consistent with these patterns, the highest values for seed traits and germination parameters in the present study were generally obtained from the Eskikale provenance, whereas the Tortum provenance exhibited the lowest values. The lower performance observed in the Tortum provenance may also be associated with the shorter vegetation period at higher elevations, which can limit seed development and maturation processes.

In addition, maternal environmental effects are known to play a crucial role in shaping seed traits. Environmental conditions experienced by mother plants during flowering and seed maturation may influence seed development and subsequently affect seed size, weight, and quality. Such maternal effects may lead to considerable variation in seed characteristics among populations of the same species growing under different ecological conditions [46]. These differences are ecologically important because seed size and mass are often associated with seedling vigor and establishment success in natural regeneration and restoration programs [47].

Therefore, the variation in seed morphometric traits observed among the *C. coggygria* provenances in this study may reflect the combined influence of genetic differentiation among populations and the climatic conditions prevailing at the seed source locations. Understanding these provenance-related differences is important for selecting suitable seed sources for afforestation and ecological restoration programs.

4.2. Germination Responses in Relation to Provenance and Seed Size

The results showed that the germination percentage and mean germination time were significantly affected by provenance, suggesting that dormancy intensity may also differ among provenances within a species, as noted by Harrington et al. [48]. In contrast, seed size had no significant effect on any of the parameters. Thus, seed size was not a significant factor determining the germination success of *C. coggygria* seeds in this study.

Silva et al. [49] noted that seed propagation in *C. coggygria* is limited by dormancy-related constraints, which may complicate germination responses. The seeds of *C. coggygria* exhibit a combination of physical and physiological dormancy, and overcoming these germination barriers generally requires chemical scarification in sulfuric acid (H_2SO_4), followed by cold stratification [12]. Studies have reported that the sulfuric acid scarification time, which has yielded successful results, generally ranges from 20 to 60 min, while the cold stratification period ranges from 30 to 120 days [10–12,39,49,50]. In this study, pretreatments generally increased the germination percentage. Although the germination percentages were higher in the pretreated groups than in the control group, no statistically significant difference was observed between the pretreatment types.

These results demonstrate that responses to stratification duration exhibited provenance-specific variation. Moreover, the limited change in the mean germination time suggests that the pretreatments primarily enhanced the germination percentage rather than accelerating the germination process. The extremely low germination percentages recorded in the control group across all provenances confirm the strong physical and physiological dormancy characteristics of *C. coggygria* seeds.

Studies have reported varying results regarding the effects of seed size on germination. Some studies have reported that larger seeds have higher mean germination times than smaller ones [51,52]. Conversely, some studies have shown that seed size has no significant effect on germination rate [53].

In the present study, the effect of seed size on germination varied among the provenances. For example, small seeds from Eskikale showed slightly higher germination percentages than large seeds, whereas in the Tortum provenance, the opposite trend was observed. In contrast, seeds from Tepekoy and Seyitler exhibited relatively similar germination responses between seed size classes. These differences did not indicate a consistent trend among provenances.

Overall, the results indicate strong dormancy requiring pretreatments for all provenances, with no uniform or provenance-independent effect of seed size on the germination rate. Although seed size did not show a consistent effect on germination percentage in this study, it may still influence germination dynamics such as the timing of germination.

In terms of mean germination time, some provenances indicate that smaller seeds may germinate faster than larger seeds [54]. Conversely, although larger seeds germinate more slowly, their overall germination potential may be higher [55]. Similarly, some studies have reported that smaller seeds yield better mean germination times [54]. In a long-term field study conducted on nine tree species, seedlings originating from smaller seeds exhibited higher relative height growth during their first year [56].

Maleki et al. [57] reported that seed dormancy is strongly associated with seed mass. However, contrary to expectations, in this study, larger seeds did not consistently germinate more rapidly or at a higher rate. This outcome is likely attributable to interactions among growth form, dormancy type, and phylogenetic history.

In the present study, different combinations of 20–40 min of sulfuric acid application and 30–60 d of cold stratification were tested based on methods reported to have high germination success in previous studies [10,11,39]. The results revealed that the applied pretreatments increased the germination percentage but had no statistically significant effect on the mean germination time. Additionally, no statistically significant differences were observed in germination percentage among the applied pretreatment combinations. Therefore, it can be concluded that the pretreatments used in this study may be effective in eliminating germination barriers in *C. coggygria* seeds, but there was no significant difference in germination success among the different treatments tested.

4.3. Seedling Morphological Variation in Relation to Provenance and Seed Size

Seedling height and root collar diameter significantly affect seedling survival and post-sowing development. Existing research indicates that taller seedlings with thicker diameters exhibit higher survival and development under field conditions [27]. Environmental factors and provenance-specific genetic variations may influence morphological development. These results suggest that the effect of seed size on seedling growth is not the sole determinant but should be evaluated in conjunction with other factors, such as provenance.

C. coggygria is a widely preferred outdoor ornamental plant in landscaping applications. Therefore, good seedling development is an important aesthetic consideration. Large seeds are generally preferred for obtaining larger seedlings [23]. In this study, we predicted that larger seeds would yield more developed seedlings than smaller ones. However, the results revealed that seed size only affected seedling and root dry weights and had no significant effect on other morphological characteristics of the seedlings. Similarly, some studies have reported that seed size has no significant effect on germination characteristics and seedling development [38].

Seed size is directly associated with the amount of nutrient reserves available for the development of young seedlings [54]. In this context, it has been reported that large seeds tend to produce more vigorous seedlings than small seeds [21]. However, plants optimize their resource use according to environmental conditions. According to the resource optimization hypothesis, plants tend to allocate fewer resources to root development in environments with abundant nutrients [58,59]. In this scenario, seedlings derived from larger seeds are expected to exhibit a lower root proportion due to the greater nutrient reserves contained in larger seeds [54]. In the present study, this expected pattern was observed for the Eskikale, Tepekoy, and Seyitler provenances. However, a different trend was detected in the Tortum provenance, where seedlings produced from large seeds exhibited higher root dry weight than those derived from small seeds.

Seed size plays a critical role in regulating water uptake dynamics during germination [60]. Larger seeds are generally less permeable because they have a lower surface-to-volume ratio than smaller seeds, which limits their water absorption rate. Seed size is typically associated with seed-coat thickness; as seed size increases, seed-coat thickness also tends to increase, contributing to reduced permeability and slower imbibition rates. Consequently, larger seeds often exhibit delayed water uptake, prolonged mean germination times, and slower initiation of germination. In contrast, smaller seeds, characterized by thinner seed coats and a higher surface-to-volume ratio, are more permeable and capable of absorbing water more efficiently, resulting in a faster onset of germination [51,60]. However, the results of this study did not show a statistically significant effect of seed size on mean germination time, suggesting that differences in seed coat permeability may not have been sufficiently large to influence germination timing in *C. coggygria*.

Seedlings obtained from early-germinating seeds are expected to reach higher heights and root dry weights because of their longer developmental period. However, considering that seed size did not significantly affect the mean germination time in this study, it is unlikely that the higher dry weights obtained from small seeds can be attributed to early seed germination.

The morphological characteristics of *C. coggygria* seedlings vary according to seed provenance. Statistically significant differences were observed among the provenances, particularly in seedling height and root collar diameter. Seedlings produced from Eskikale and Seyitler provenances had higher seedling heights and root collar diameters than those from other provenances. However, no significant differences were observed among the provenances in terms of root, stem, or total seedling dry weight. Considering these provenance-related differences in seedling morphology, the ecological significance of seedling height becomes particularly important for field establishment.

Consistent with the patterns observed in seed traits, a similar trend was also reflected in the morphological characteristics of the seedlings. The highest values for seedling height, root collar diameter, and other morphological traits were obtained from the Eskikale provenance. In contrast, the Tortum provenance, which has the highest elevation and the lowest precipitation and temperature values among the study sites, exhibited the lowest values for seedling morphological traits. Similar provenance-related differences in early seedling growth and morphology have been reported for several forest tree species [43]. These findings indicate that the observed variation in seedling morphology may be influenced not only by genetic differences but also by the elevation of the provenance sites and the associated climatic conditions.

Although seedlings were grown in the Seyitler nursery, the best morphological performance was observed in the Eskikale provenance rather than the local Seyitler provenance. This finding suggests that local populations are not always superior in terms of growth performance. Provenance trials have frequently demonstrated that non-local populations may grow faster under common garden conditions due to genetic variation in growth strategies and climatic adaptation [61,62]. Local populations may be better adapted to long-term survival under natural environmental stresses, whereas populations originating from different climatic conditions may express higher growth potential under favorable nursery conditions. In addition, the seeds originating from the Eskikale provenance were significantly larger than those from the Seyitler provenance, which may also have contributed to the superior morphological development of the seedlings. Larger seeds generally contain greater nutrient reserves, which can support early seedling growth and promote the development of larger seedlings during the initial stages of establishment [47–63]. Therefore, the superior seedling morphology observed in the Eskikale provenance may partly reflect both genetic differences among provenances and the larger seed size associated with this provenance.

When *C. coggygria* seedlings are planted in areas with dense live cover and adequate rainfall, tall seedlings are crucial. Seedling height is a key indicator of successful establishment in the field. Tall seedlings are reported to be more successful, particularly in areas with dense live cover, animal damage, frost, and soil erosion [64]. In an evaluation of sites where seedling height provides an advantage, Eskikale and Seyitler were identified as the provenances that produced the tallest seedlings.

Seedlings with thicker root collars generally develop stronger root systems and store more nutrients, making them more resilient in arid areas [65,66]. In this context, seedlings from the Eskikale, Tepekoy, and Seyitler provenances had higher root collar diameters than those from Tortum. Therefore, the higher root collar diameter values observed in the Eskikale, Tepekoy, and Seyitler provenances may indicate a greater potential for survival and establishment under water-limited conditions.

4.4. Variation in Seedling Quality Indices in Relation to Provenance and Seed Size

To date, no studies have investigated root mass fractions in shrubby species such as *C. coggygria*. However, in studies conducted on some tree species, root mass fraction values were determined in one-year-old seedlings. For example, values have been reported to range from 31.19% to 34.19% in stinking juniper [67], 15% to 48% in common cypress [68], 28% in stone pine [69], and 33% to 39% in prickly juniper [70]. In this study, the root mass fraction in *C. coggygria* seedlings varied between 80.25% and 82.78% depending on provenance, and between 81.30% and 81.60% depending on seed size. The observed values were significantly greater than those documented for other tree species, highlighting the morphological advantages of *C. coggygria*. This morphological trait shows a strong potential for success, especially in applications related to erosion control, and supports its use in dry regions.

In this study, the shoot/root ratio, which is the ratio of stem to root weight used to assess the morphology of seedlings, ranged from 0 to 1. This is because, in all provenances, the dry weights of the roots exceeded those of the stems. The literature indicates that seedlings with a shoot/root ratio of 2 or 3 can effectively compensate for water lost through transpiration through their root systems and, for this reason, have a higher retention success in arid areas [27]. In this regard, the greater root weight than stem weight in *C. coggygria* seedlings indicates a significant advantage for use under arid conditions. In contrast, a sturdiness index value below 50 indicates that the seedlings can be considered of high quality [27]. In this study, sturdiness index values ranging from 15.13 to 22.94 were obtained depending on the provenance, and in line with these values, it can be argued that all seedlings are morphologically in the "high-quality seedling" category.

5. Conclusions

This study aimed to determine whether there were significant differences in the germination characteristics and morphological development of the seedlings of *C. coggygria*, a naturally occurring shrub species in the Artvin region, across different provenances and seed size classes. These findings provide important data on the production and afforestation potential of this species at both seed and seedling levels.

In terms of seed traits, the Eskikale provenance achieved statistically higher values than the other provenances in terms of seed width, length, thickness, and 1000-seed weight. This result places the Eskikale provenance at the forefront in terms of seed supply. However, higher seed morphological values did not provide a direct advantage in terms of germination percentage, mean germination time, or seedling development rate. Similarly, seed size did not significantly affect the germination percentage or mean germination time.

The high percentage of empty seeds in *C. coggygria* is one of the main factors that negatively affect germination success. Therefore, physical separation by flotation is essential before attempting the propagation of these species. All treatments, including chemical scarification with H_2SO_4 and subsequent cold stratification, aimed to eliminate germination barriers and significantly increased the mean germination time compared with the control group. Although no statistically significant differences in germination success were observed among the pretreatments, considering the effects of application duration and seed origin, it is recommended to employ a combination of 20 min of H_2SO_4 treatment followed by 60 days of cold stratification.

In evaluating seedling morphological traits, the origin of the seeds significantly influenced key quality metrics, such as seedling height and root collar diameter. Notably, seedlings from the Eskikale and Seyitler origins exhibited statistically superior values for these traits, rendering them preferable for cultivating tall seedlings in nurseries compared to the other origins.

Seed size affected root dry weight and total seedling dry weight, with seedlings originating from smaller seeds exhibiting higher values for these traits. This finding indicates that smaller seeds can be effectively used for seedling production. However, additional studies incorporating a wider range of seed size classes would help clarify this relationship.

All provenances achieved root mass fraction values exceeding 80%, indicating that *C. coggygria* seedlings have the potential to develop a robust and deep root system, even at an early stage. These values are notably higher than the root percentages of many previously reported tree species. Given that the root weight surpasses the stem weight, this species is considered a promising candidate for adaptation to arid environments and erosion control.

The shoot/root ratio values, which reflect the ratio of stem to root dry weights, ranged from 0.22 to 0.31, with root weights exceeding stem weights for all provenances. This indicates that *C. coggygria* has a high capacity to compensate for water loss when it is planted in arid areas. The sturdiness index values remained below 50 in all groups, and in this way, all seedlings met the morphological criteria for "high-quality seedlings".

C. coggygria shows considerable potential for dryland afforestation and specialized forestry practices, such as erosion control, owing to its high germination capacity, well-developed root system, and provenance-related morphological variation. To confirm this potential, field-based evaluations of seedling performance under natural conditions and long-term monitoring are required. In addition, future studies that incorporate a broader classification of seed size classes across a wider range of populations would improve our understanding of the species' adaptive traits and support more informed selection for afforestation programs.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/horticulturae12040426/s1, Table S1. Analysis of variance results for seed length (L), width (W), thickness (T), and seed volume (V) as affected by provenance and seed size classes, Table S2. Analysis of variance results for arithmetic mean diameter (Da), geometric mean diameter (Dg), sphericity (Sp), and thousand seed weight (TSW) of the seeds as affected by provenance and seed size classes, Table S3. Results of variance analysis regarding whether germination percentage and mean germination time differ according to provenance, seed size and pretreatment differences, Table S4. Results of variance analysis of differences between provenance and seed size groups according to seedling morphological characteristics, Table S5. Results of variance analysis showing whether there are differences between provenances and seed size groups according to the percentage of dry roots, shoot/root ratio and sturdiness Index of seedlings.

Author Contributions: Conceptualization, A.G. and A.S.; methodology, A.G.; software, A.G.; validation, A.G. and A.S.; formal analysis, A.G.; investigation, A.G. and A.S.; resources, A.G.; data curation, A.G.; writing—original draft preparation, A.G.; writing—review and editing, A.G.; visualization, A.G.; supervision, A.G.; project administration, A.G.; funding acquisition, A.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The datasets have not been deposited in a public repository; however, the data supporting the findings of this study are available from the corresponding author upon request.

Acknowledgments: During the preparation of this manuscript, the authors used ChatGPT (version 5.2) and Paperpal solely for language editing purposes, including grammatical correction, checking sentence clarity, and improving the overall readability of the text. These tools were not used for study design, data collection, data analysis, interpretation of results, or drawing conclusions. All the AI-generated outputs were carefully reviewed and edited by the authors, who take full responsibility for the scientific content and conclusions of this publication.

Conflicts of Interest: The authors declare no conflicts of interest. No external funding was received for this study.

Abbreviations

The following abbreviations are used in this manuscript:

C. coggygria	*Cotinus coggygria*
GP	Germination Percentage
MGT	Mean Germination Time
SH	Seedling Height
RCD	Root Collar Diameter
DRW	Dry Root Weight
DSW	Dry Stem Weight
SDW	Seedling Dry Weight
TDW	Total Dry Weight
RMF	Root Mass Fraction
S:R	Shoot/Root Ratio
SI	Sturdiness Index
Da	Arithmetic Mean Diameter
Dg	Geometric Mean Diameter
Sp	Sphericity
V	Seed Volume
TSW	Thousand-Seed Weight
H_2SO_4	Sulfuric Acid
CS	Cold Stratification

References

1. Marčetić, M.; Božić, D.; Milenković, M.; Malešević, N.; Radulović, S.; Kovačević, N. Antimicrobial, antioxidant and anti-inflammatory activity of young shoots of the smoke tree (*Cotinus coggygria* Scop.). *Phytother. Res.* **2013**, *27*, 1658–1663. [CrossRef] [PubMed]
2. Stanković, M.; Zlatić, N.; Locatelli, M.; Perrucci, M.; Marković, T.; Jakovljević, D. Comprehensive study of habitat substrate-related variability of *Cotinus coggygria* Scop. as a valuable source of natural bioactive compounds. *Plants* **2025**, *14*, 2695. [CrossRef] [PubMed]
3. Zhang, Z.; Yan, X.; Guo, C.; Dong, W.; Zhao, L.; Liu, D. Changes in the suitable habitat of the smoke tree (*Cotinus coggygria* Scop.), a species with an East Asian–Tethyan disjunction. *Plants* **2025**, *14*, 547. [CrossRef]
4. Tzakou, O.; Bazos, I.; Yannitsaros, A. Essential oils of leaves, inflorescences and infructescences of spontaneous *Cotinus coggygria* Scop. from Greece. *Flavour Fragr. J.* **2005**, *20*, 531–533. [CrossRef]
5. Tunç, K.; Hoş, A.; Güneş, B. Investigation of antibacterial properties of *Cotinus coggygria* from Turkey. *Pol. J. Environ. Stud.* **2013**, *22*, 1559–1561.
6. Ulukanli, Z.; Karabörklü, S.; Bozok, F.; Cenet, M.; Öztürk, B.; Balcilar, M. Antimicrobial, insecticidal and phytotoxic activities of *Cotinus coggygria* Scop. essential oil (Anacardiaceae). *Nat. Prod. Res.* **2014**, *28*, 2150–2157. [CrossRef]
7. Shagun, S.; Bhattacharya, S.; Sharma, M. Chemical profiling, antioxidant and antibacterial properties of *Cotinus coggygria* essential oil from Western Himalaya. *Int. J. Pharmacogn. Phytochem. Res.* **2016**, *8*, 1183–1186.
8. Matić, S.; Stanić, S.; Mihailović, M.; Bogojević, D. *Cotinus coggygria* Scop.: An overview of its chemical constituents, pharmacological and toxicological potential. *Saudi J. Biol. Sci.* **2016**, *23*, 452–461. [CrossRef]
9. Xiang, D.; Zhang, G.; Gong, R.; Di, B.; Tian, Y. Effect of cadmium stress on growth and electrical impedance spectroscopy parameters of *Cotinus coggygria* roots. *Water Air Soil Pollut.* **2018**, *229*, 279. [CrossRef]
10. Ölmez, Z.; Yahyoglu, Z.; Temel, F.; Gokturk, A. Effects of some pretreatments on germination of bladder-senna (*Colutea armena* Boiss. and Huet.) and smoke-tree (*Cotinus coggygria* Scop.) seeds. *J. Environ. Biol.* **2008**, *29*, 319–323.
11. Ölmez, Z.; Gokturk, A.; Karaşah, B.; Yilmaz, H. Effects of cold stratification and sulphuric acid pretreatments on germination of three provenances of smoke-tree (*Cotinus coggygria* Scop.) seeds in greenhouse and laboratory conditions. *Afr. J. Biotechnol.* **2009**, *8*, 4964–4968.
12. Pipinis, E.; Milios, E.; Tomazos, N.; Smiris, P. Breaking dormancy and germination of *Cotinus coggygria* Scop. seeds by means of sulphuric acid scarification, cold stratification and gibberellic acid. *Silva Balcanica* **2014**, *15*, 38–46.
13. Demirci, B.; Demirci, F.; Başer, K.H.C. Composition of the essential oil of *Cotinus coggygria* (Scop.) from Turkey. *Flavour Fragr. J.* **2003**, *18*, 43–44. [CrossRef]
14. Koleva, V.; Chilev, C.; Penchev, I.; Simeonov, E. Leaching of polyphenols and flavonoids from *Cotinus coggygria*. In *Scientific Works of UFT*; University of Food Technologies: Plovdiv, Bulgaria, 2012; Volume LIX, pp. 201–203.

15. Ivanova, D.; Pavlov, D.; Eftimov, M.; Kalchev, K.; Nashar, M.; Tzaneva, M.; Valcheva-Kuzmanova, S. Subchronic toxicity study of ethanol infusion from *Cotinus coggygria* wood in rats. *Bulg. J. Agric. Sci.* **2013**, *19*, 182–185.
16. Gokturk, A.; Olmez, Z.; Temel, F. Some native plants for erosion control efforts in Coruh River Valley. *Pak. J. Biol. Sci.* **2006**, *9*, 667–673. [CrossRef]
17. Bischoff, A.; Vonlanthen, B.; Steinger, T.; Müller-Schärer, H. Seed provenance matters: Effects on germination of four plant species used for ecological restoration. *Basic Appl. Ecol.* **2006**, *7*, 347–359. [CrossRef]
18. Bonner, F.T. Seed biology. In *The Woody Plant Seed Manual*; Bonner, F.T., Karrfalt, R.P., Eds.; Agriculture Handbook No. 727; United States Department of Agriculture, Forest Service: Washington, DC, USA, 2008; pp. 1–39.
19. Mölken, T.; Jorritsma-Wienk, L.D.; Hoek, P.H.; Kroon, W.H. Only seed size matters for germination in different populations of the dimorphic *Tragopogon pratensis* subsp. *pratensis* (Asteraceae). *Am. J. Bot.* **2005**, *92*, 432–437. [CrossRef] [PubMed]
20. Murali, K.S. Patterns of seed size, germination and seed viability of tropical tree species in southern India. *Biotropica* **1997**, *29*, 271–279. [CrossRef]
21. Yanlong, H.; Mantang, W.; Shujun, W.; Yanhui, Z.; Tao, M.; Guozhen, D. Seed size effect on seedling growth under different light conditions in the clonal herb *Ligularia virgaurea* in the Qinghai–Tibet Plateau. *Acta Ecol. Sin.* **2007**, *27*, 3091–3108.
22. Tilki, F.; Yuksek, F.T.; Guner, S. The effect of undercutting on growth and morphology of 1+0 bareroot sessile oak seedlings in relation to acorn size. *Aust. J. Basic Appl. Sci.* **2009**, *3*, 3900–3905.
23. Cicek, E.; Tilki, F. Seed size effects on germination, survival and seedling growth of *Castanea sativa* Mill. *J. Biol. Sci.* **2007**, *7*, 438–441. [CrossRef]
24. Aksu, Y.; Tilki, F. Effects of provenance and seed size on seedling survival and morphology of *Quercus pontica*. *Artvin Coruh Univ. J. For. Fac.* **2015**, *16*, 216–226. [CrossRef]
25. Mirgal, A.B.; Gunaga, R.P.; Salunkhe, C.B. Seed size and its influence on germination, seedling growth and biomass in *Saraca asoca* (Roxb.) de Wilde, a critically endangered tree species of the Western Ghats, India. *J. Appl. Nat. Sci.* **2016**, *8*, 1599–1602. [CrossRef]
26. Sisay, T.; Alemu, A.; Mariam, Y.G. Quality of tree seedlings across different nursery ownerships in Central Gondar Zone, Ethiopia. *J. Hortic. For.* **2020**, *12*, 84–93. [CrossRef]
27. Genç, M.; Yahyaoğlu, Z. Kalite sınıflamasında kullanılan özellikler ve tespiti. In *Fidan Standardizasyonu*; Genç, M., Yahyaoğlu, Z., Eds.; No. 775; Süleyman Demirel Üniversitesi Orman Fakültesi Yayın: Isparta, Turkey, 2007; pp. 353–466.
28. Mohsenin, N.N. *Physical Properties of Plant and Animal Materials: Structure, Physical Characteristics and Mechanical Properties*; Gordon and Breach Science Publishers: New York, NY, USA, 1970; pp. 1–742.
29. Jain, R.K.; Bal, S. Properties of pearl millet. *J. Agric. Eng. Res.* **1997**, *66*, 85–91. [CrossRef]
30. International Seed Testing Association (ISTA). Thousand-Seed Weight (TSW) Determination. In *International Rules for Seed Testing: Chapter 10*; Version 8; ISTA: Bassersdorf, Switzerland, 2019; pp. 1–2.
31. International Seed Testing Association (ISTA). *International Rules for Seed Testing*; International Seed Testing Association (ISTA): Bassersdorf, Switzerland, 2018.
32. Bewley, J.D.; Bradford, K.J.; Hilhorst, H.W.M.; Nonogaki, H. *Seeds: Physiology of Development, Germination and Dormancy*, 3rd ed.; Springer: New York, NY, USA, 2013.
33. Zida, D.; Tigabu, M.; Sawadogo, L.; Odén, P.C. Initial seedling morphological characteristics and field performance of two Sudanian savanna species in relation to nursery production period and watering regimes. *For. Ecol. Manag.* **2008**, *255*, 2151–2162. [CrossRef]
34. Easdale, T.A.; Richardson, S.J.; Marden, M.; England, J.R.; Gayoso-Aguilar, J.; Guerra-Cárcamo, J.E.; McCarthy, J.K.; Paula, K.I.; Schwendenmann, L.; Brandon, A.M. Root biomass allocation in southern temperate forests. *For. Ecol. Manag.* **2019**, *453*, 117542. [CrossRef]
35. Bernier, P.Y.; Lamhamedi, M.S.; Simpson, D.G. Shoot: Root ratio is of limited use in evaluating the quality of container conifer stock. *Tree Plant. Notes* **1995**, *46*, 102–106.
36. Thompson, B.E. Seedling morphological evaluation: What you can tell by looking. In *Evaluating Seedling Quality: Principles, Procedures, and Predictive Ability of Major Tests*; Duryea, M.L., Ed.; Oregon State University: Corvallis, OR, USA, 1985; pp. 55–71.
37. Aphalo, P.; Rikala, R. Field performance of silver-birch planting stock grown at different spacing and in containers of different volume. *New For.* **2003**, *25*, 93–108. [CrossRef]
38. Khera, N.; Saxena, A.K.; Singh, R.P. Seed size variability and its influence on germination and seedling growth of five multipurpose tree species. *Seed Sci. Technol.* **2004**, *32*, 319–330. [CrossRef]
39. Guner, S.; Tilki, F. Dormancy breaking in *Cotinus coggygria* Scop. seeds of three provenances. *Sci. Res. Essays* **2009**, *4*, 73–77.
40. Yilmaz, T.; Yilmaz, M. Researches on the seed traits of relict common alder (*Alnus glutinosa* (L.) Gaertn.) populations in the Eastern Mediterranean region. *Turk. J. For. Sci.* **2021**, *5*, 150–164. [CrossRef]
41. Gokturk, A.; Guner, S. Effect of elevation on morphological characteristics and germination of black alder (*Alnus glutinosa* subsp. *barbata*) seeds. *Kastamonu Univ. J. For. Fac.* **2024**, *24*, 13–21. [CrossRef]

42. Loha, A.; Tigabu, M.; Teketay, D.; Lundkvist, K.; Fries, A. Provenance variation in seed morphometric traits, germination, and seedling growth of *Cordia africana* Lam. *New For.* **2006**, *32*, 71–86. [CrossRef]
43. Fredrick, C.; Muthuri, C.; Ngamau, K.; Sinclair, F. Provenance variation in seed morphological characteristics, germination and early seedling growth of *Faidherbia albida*. *J. Hortic. For.* **2015**, *7*, 127–140.
44. Pers-Kamczyc, E.; Suszka, J. Long-term maternal fertilizer addition increased seed size but decreased germination capacity and offspring performance in *Taxus baccata* L. *Forests* **2022**, *13*, 670. [CrossRef]
45. Baskin, C.C.; Baskin, J.M. *Seeds: Ecology, Biogeography, and Evolution of Dormancy and Germination*, 2nd ed.; Academic Press: San Diego, CA, USA, 2014.
46. Roach, D.A.; Wulff, R.D. Maternal effects in plants. *Annu. Rev. Ecol. Syst.* **1987**, *18*, 209–235. [CrossRef]
47. Moles, A.T.; Westoby, M. Seedling survival and seed size: A synthesis of the literature. *J. Ecol.* **2004**, *92*, 372–383. [CrossRef]
48. Harrington, C.A.; Brodie, L.C.; DeBell, D.S.; Schopmeyer, C.S. Alnus P. Mill. (Alder). In *The Woody Plant Seed Manual*; Bonner, F.T., Karrfalt, R.P., Eds.; Agriculture Handbook No. 727; United States Department of Agriculture, Forest Service: Washington, DC, USA, 2008; pp. 232–242.
49. Silva, J.A.T.; Pacholczak, A.; Ilczuk, A. Smoke tree (*Cotinus coggygria* Scop.) propagation and biotechnology: A mini-review. *S. Afr. J. Bot.* **2018**, *114*, 232–240. [CrossRef]
50. Palizdar, M.; Panahi, P.; Noghani, Z.; Pourhashemi, M. Some strategies for improvement of seed germination of smoke-tree (*Cotinus coggygria* Scop.), an endemic species of the Arasbaran forests. *Iran. J. For.* **2014**, *6*, 244–252.
51. Kulaç, Ş.; Özbayram, A.K.; Değirmenci, Z.; Dudu Küçük, E.; Karadağ, A. Effect of chestnut seed size on germination percentage and morphology of seedlings. *Duzce Univ. J. For. Fac.* **2015**, *10*, 36–42.
52. Attri, V.; Brar, P.S.; Saralch, H.S. Effect of seed size and presowing treatments on germination, early seedling growth and seedling vigour of *Senegalia catechu* (L.f.) P.J.H. Hurter & Mabb. in nursery condition. *Bhartiya Krishi Anusandhan Patrika* **2025**, *40*, 158–165. [CrossRef]
53. Tumpa, K.; Vidaković, A.; Drvodelić, D.; Šango, M.; Idžojtić, M.; Perković, I.; Poljak, I. The effect of seed size on germination and seedling growth in sweet chestnut (*Castanea sativa* Mill.). *Forests* **2021**, *12*, 858. [CrossRef]
54. Souza, M.L.; Fagundes, M. Seed size as key factor in germination and seedling development of *Copaifera langsdorffii* (Fabaceae). *Am. J. Plant Sci.* **2014**, *5*, 2566–2573. [CrossRef]
55. Fagundes, M.; Silva, M.I.R.; Mayrink, B.H.S.; Kenedy-Siqueira, W.; Figueiredo, L.H.A.; Cornelissen, T. Linking seed size and thermal tolerance in seed germination of *Hymenaea stigonocarpa*, a fire-prone Neotropical savanna tree. *Seeds* **2025**, *4*, 54. [CrossRef]
56. Macera, L.G.; Pereira, S.R.; de Souza, A.L.T. Survival and growth of tree seedlings as a function of seed size in a gallery forest under restoration. *Acta Bot. Bras.* **2017**, *31*, 539–545. [CrossRef]
57. Maleki, K.; Vandelook, F.; Saatkamp, A.; Heshmati, S.; Soltani, E. Global patterns in the evolutionary relations between seed mass and germination traits. *Ecol. Evol.* **2025**, *15*, e71543. [CrossRef]
58. Ågren, G.I.; Franklin, O. Root: Shoot ratios, optimization and nitrogen productivity. *Ann. Bot.* **2003**, *92*, 795–800. [CrossRef]
59. Yang, Z.; Midmore, D.J. Modelling plant resource allocation and growth partitioning in response to environmental heterogeneity. *Ecol. Model.* **2005**, *181*, 59–77. [CrossRef]
60. Upretee, P.; Bandara, M.S.; Tanino, K.K. The role of seed characteristics on water uptake preceding germination. *Seeds* **2024**, *3*, 559–574. [CrossRef]
61. Bischoff, A.; Steinger, T.; Müller-Schärer, H. The importance of plant provenance and genotypic diversity of seed material used for ecological restoration. *Restor. Ecol.* **2009**, *17*, 668–675. [CrossRef]
62. Petrík, P.; Grote, R.; Gömöry, D.; Kurjak, D.; Petek-Petrik, A.; Lamarque, L.J.; Sliacka Konôpková, A.; Mukarram, M.; Debta, H.; Fleischer, P., Jr. The role of provenance for the projected growth of juvenile European beech under climate change. *Forests* **2023**, *14*, 26. [CrossRef]
63. Westoby, M.; Leishman, M.; Lord, J. Comparative ecology of seed size and dispersal. *Philos. Trans. R. Soc. B* **1996**, *351*, 1309–1318. [CrossRef]
64. Landhäusser, S.M.; Wiley, E.T.; Solarik, K.A.; Kulbaba, S.P.; Goeppel, A.E. The importance of initial seedling characteristics in controlling allocation to growth and reserves under different soil moisture conditions. *Forests* **2023**, *14*, 796. [CrossRef]
65. Valdés-Rodríguez, O.A.; Pérez-Vázquez, A. Seedling characteristics of three oily species before and after root pruning and transplant. *Plants* **2019**, *8*, 258. [CrossRef] [PubMed]
66. Novikova, T.P.; Tylek, P.; Mastrangelo, C.B.; Drapalyuk, M.V.; Kharin, S.V.; Novikov, A.I. The root collar diameter growth reveals a strong relationship with the height growth of juvenile Scots pine trees from seeds differentiated by spectrometric feature. *Forests* **2023**, *14*, 1164. [CrossRef]
67. Özüberk, Ş.D.; Deligöz, A. Effects of seedbed density on morphology, root growth potential and carbohydrate content of stinking juniper (*Juniperus foetidissima* Willd.) seedlings. *Suleyman Demirel Univ. J. Nat. Appl. Sci.* **2016**, *20*, 369–375. [CrossRef]
68. Ayan, S.; Civek, E.; Yer Çelik, E.N.; Gülseven, O.; Akın, Ş.S.; Yılmaz, E. Morphological Quality Characteristics of Mediterranean and Arizona Cypresses Seedlings. *Bartin Univ. J. For. Fac.* **2020**, *22*, 580–590. [CrossRef]

69. Ayan, S.; Civek, E.; Yer Çelik, E.N.; Gülseven, O.; Özel, H.B.; Eshaibi, J.A.H.; Akın, Ş.S.; Yılmaz, E. Morphological Quality Characteristics of Different Ages Containerised Seedlings of Stone Pine (*Pinus pinea* L.). *Bartin Univ. J. For. Fac.* **2020**, *22*, 633–641. [CrossRef]
70. Alim, E.; Kavgacı, A. The effects of cultivation density on morphological characteristics of prickly juniper (*Juniperus oxycedrus* L. subsp. *oxycedrus*) seedlings in Eğirdir Forest Nursery. *J. For. Res.* **2017**, *4*, 1–11. [CrossRef]

https://doi.org/10.3390/horticulturae12040426