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Growth character responses of oriental beech (*Fagus orientalis* Lipsky) seedlings to nanotechnological fertiliser applications

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Abstract

High-quality seedling production is crucial in forestry activities to enhance the success of planting efforts and ensure the sustainability of the species. In this study, the effects of different concentrations (0, 4, 8, and 12 mL/L) of nanotechnological liquid organomineral fertiliser on the morphological characteristics and seedling quality of two-year-old oriental beech (*Fagus orientalis* Lipsky) seedlings were investigated. Morphological characteristics measured in the study included seedling height, root collar diameter, number of side branches, root length, root number, as well as fresh and dry weights of shoot, root, and seedling. For seedling quality evaluation, dry root percentage, sturdiness quotient, shoot-root ratio, and the Dickson quality index were used. The results showed that the highest fertiliser concentration (F12 mL/L) produced the most favourable outcomes in terms of both morphological characteristics (e.g. 42.16 cm for seedling height, 8.42 mm for root collar diameter) and quality criteria (e.g. 0.39 for the Dickson quality index). Furthermore, correlation analysis revealed strong positive correlations between simple measurable parameters, such as seedling height and root collar diameter and quality indices, such as the Dickson quality index, indicating their potential as meaningful indicators in quality assessment. The study results demonstrate that fertiliser applications can significantly contribute to producing high-quality seedlings.

Keywords: fertilisation; morphological characteristics; quality index; seedling quality

Introduction

Located entirely within the Holarctic biogeographic region (Güner et al. 2012), Turkey is home to 12,354 plant taxa (Terzioğlu et al. 2021). In Turkey, oriental beech (*Fagus orientalis* Lipsky), one of the most important primary forest tree species for national forestry, belongs to the Fagaceae family (Anonymous 1985, Anşin and Özkan 2006). The general geographical range of the oriental beech extends from the Eastern Balkan Peninsula, including Bulgaria, Romania, and Greece, as well as the Crimea, Caucasus, and Northern Iran (Yaltırık 1982). The species is primarily located along the northern slopes of the North Anatolian coastal mountains and the Istranca Mountains within the Euro-Siberian flora region in Turkey (Yurdakulol 1981, Anonymous 1985, Anşin and Özkan 2006).

Beech populations in Southern Europe, including Turkey, have faced strong environmental pressure over the past decade (Jump et al. 2006, Piovesan et al. 2008). These pressures are expected to increase in the future due to potential changes in precipitation and temperature patterns following to climate change (Charru et al. 2010, Rita et al. 2014). Therefore, concerns regarding the dynamics of beech survival in the areas where beech species grow in Europe emerged (Bréda et al. 2006, Geßler et al. 2007). Given the ongoing climate change, it has been reported that oriental beech populations in Western Eurasia will decline due to increasing drought, and that the Caucasus region, along with Northern Iran, will become a refuge for the species' range (Dagtekin et al. 2020). Considering the challenges oriental beech is projected to face in the future, the production of high-quality seedlings and their use in planting efforts are of great importance.

Nursery cultivation techniques are critical for seedling quality (Vilagrosa et al. 2003, Alım et al. 2008, Boydak and Çalışkan 2014). During the seedling cultivation stage, both nutritional and moisture conditions play decisive roles in maintaining seedling quality, with nutrients retained at this stage influencing field performance, as determined by survival and growth criteria after planting (Mattsson 1996). Although the response of seedlings to nutrient availability varies by species (Rubio et al. 2003), fertilisation and irrigation are the practices to be applied when soils cannot provide adequate nutrients and water for plants (Karaçal and Tüfenkçi 2010). Enhancing nutrient reserves in seedlings through fertilisation during the growth phase is considered a highly effective practice compared to nutrient uptake from the planting site (Tinus 1974, Binkley 1986). Fertilisation not only supports the growth and

development of plants but also enhances their resistance to pathogens by supplying the soil with adequate and readily available nutrients (Güneş et al. 2007, Servin et al. 2015).

On the other hand, since plant nutrients also affect the drought resistance of seedlings, fertilisation practices are particularly important for regions within the Mediterranean Basin (van den Driessche 1992). Through fertilisation, the addition of macronutrients such as nitrogen and phosphorus to the soil can enhance root growth potential and hydraulic conductivity of roots (Singh and Sale 2000, Trubat et al. 2006), thereby improving seedlings' water uptake capacity and consequently their drought tolerance (Reinbott and Blevins 1999, Trubat et al. 2010). From this perspective, in Turkey, where oriental beech exhibits significant distribution, fertilisation plays a crucial role in producing seedlings with enhanced resistance to biotic and abiotic stress factors.

Due to their simplicity and low cost, morphological traits are the most preferred measurements for assessing seedling quality (Ritchie 1984, Thompson 1985, Mexal and Landis 1990, Yahyaoğlu and Genç 2020). Among them, the easiest to measure are seedling height and root collar diameter (Haase 2008). In addition to commonly measured traits, morphological parameters such as shoot and root weights, along with quality indices like the shoot-root ratio, sturdiness quotient, and Dickson quality index, are also considered, allowing for a more comprehensive evaluation of seedling vigor and overall quality (Dickson et al. 1960, Ritchie 1984, Thompson 1985, Haase 2008, Pinto 2011). Numerous studies in the literature have utilized morphological characteristics in seedling quality assessments (Nyoka et al. 2018, Atar 2021, Özel et al. 2021, Güney et al. 2022).

The objective of this study is to analyse the impact of varying doses of nanotechnological liquid organomineral fertiliser on the morphological characteristics of oriental beech seedlings and to evaluate their quality through comprehensive index assessments.

Material and methods

The present study was conducted at Karadeniz Technical University (KTU), Trabzon, Turkey. The study material consisted of seedlings of oriental beech (*Fagus orientalis* Lipsky), an important forest tree species. The seeds of oriental beech, collected from 30 phenotypically superior individuals in the seed stand located in Çatak, Maçka, Trabzon, were sown using the line sowing method, with a 10-cm gap between the lines, in the sowing beds of the Research and Application Greenhouse of the Faculty of Forestry, KTU. One-year-old seedlings were grown through necessary weeding, watering, and other nursery care measures throughout the growing season. Seedlings showing extreme growth were removed at the beginning of the second growing season. From the start to the end of the second growing season, including the 15th of each month from March to September, the seedlings were treated with 4-4-6 Powfer nanotechnological liquid organomineral fertiliser having NPK produced by "Beybek Gübre". The guaranteed content of the fertiliser provided by the company is presented in Table 1.

To more accurately assess fertiliser effects, the beds were filled with nutrient-poor subsoil (5–50 cm) and

Table 1. Composition of the nanotechnological fertiliser used in the study

Component	Percentage/Range
Organic matter	20.0%
Total nitrogen	4.0%
Organic nitrogen	0.7%
Ammonium nitrogen (NH_4-N)	1.0%
Urea nitrogen (NH_2-N)	2.3%
Total phosphorus pentoxide (P_2O_5)	4.0%
Water-soluble phosphorus pentoxide (P_2O_5)	4.0%
Water-soluble potassium oxide (K_2O)	6.0%
pH	4.8–6.8

Table 2. Descriptions of morphological characteristics measured in the study

Measurement	Description	Tool	Unit
Seedling height (SH)	The distance from the root collar to the tip of the terminal shoot	Ruler	cm
Root collar diameter (RCD)	Diameter of the root collar measured at the base of the seedling	Digital caliper	mm
Side-branch number (SBN)	Number of lateral branches present on the seedling	Visual counting	branches
Root length (RL)	Length of the longest main root	Ruler	cm
Root number (RN)	Number of primary roots on each seedling	Visual counting	roots
Shoot and root fresh weights (ShFW, RFW)	Weight of the shoot and root immediately after separation	Precision scale	g
Shoot and root dry weights (ShDW, RDW)	Weight of the shoot and root after drying in an oven at 102 ± 2°C for 24 hours	Precision scale	g
Seedling fresh and dry weights (SdFW, SdDW)	Calculated by summing the fresh or dry weights of the shoot and root	Precision scale	g
Dry root percentage (DRP)	Calculated as the dry root weight divided by the seedling dry weight, multiplied by 100	Formula	%
Sturdiness quotient (SQ)	Seedling height (in mm) divided by the root collar diameter (in mm)	Formula	-
Shoot-root ratio (S/R)	Shoot dry weight divided by root dry weight	Formula	-
Dickson quality index (DQI)	Seedling dry weight divided by the sum of the sturdiness quotient and shoot/root ratio	Formula	-

covered with a 5 cm forest topsoil layer to support early rooting of seedlings. Pre-experiment analysis showed that the topsoil contained 1.81% organic carbon and 0.05% total nitrogen, while the subsoil, which served as the primary rooting medium for the seedlings, had 0.04% organic carbon and 0.03% total nitrogen. The treatments consisted of 0 (control), 4, 8, and 12 mL/L concentrations of a nanotechnological liquid organomineral fertiliser (F4, F8, and F12 mL/L, respectively). The experiment followed a randomised block design with three replications, using a total of 240 seedlings (4 treatments × 20 seedlings × 3 replicates). For each treatment, 5-litre fertiliser solutions were prepared and applied to 60 seedlings by pouring the solution from above using a watering can. This application method allowed the solution to contact the foliage before draining into the soil, resulting in a combined foliar and soil application. In addition to fertilisation treatments, regular watering and weeding were also carried out throughout the study. At the end of the second growing season, the following morphological measurements were performed on two-year-old oriental beech seedlings (Table 2).

For high-quality seedlings with a high survival rate, it is generally desired for the dry root percentage to be high (Johnsen et al. 1988, Alım and Kavgacı 2017). It has been reported that sturdiness quotient values above 60 (mm/mm) are not desirable, as they indicate low-quality seedlings; those between 50–60 correspond to moderate quality, and those below 50 indicate high-quality seedlings (Jaenicke 1999, Aphalo and Rikala 2003, Yahyaoğlu and Genç 2020). Moreover, a shoot-to-root ratio of ¼ to ½ is a good ratio, indicating a healthy individual (Jaenicke 1999). In addition, it has been noted that Dickson quality index values close to or greater than 1 indicate high quality of seedlings (Dickson et al. 1960, Aslan 1986).

The data obtained from the study were subjected to variance analysis (one-way ANOVA) and Duncan's multiple range test using the IBM SPSS Statistics 27 software package (IBM 2020). Variance analysis was conducted to determine whether there was a statistically significant difference in each morphological characteristic based on the fertiliser treatments. Additionally, Duncan's test was applied to identify the groups formed among the treatments as a result of these differences. Furthermore, a correlation analysis was performed using the R Studio software for statistical computing (Posit 2021) to reveal the direction and strength of the relationships between the measured morphological characteristics.

Results

The means of seedling height, root collar diameter, number of side-branches, root length, and number of roots for two-year-old oriental beech seedlings, along with the results of the variance analysis and Duncan's test, are presented in Figure 1.

The highest values in terms of seedling height and root collar diameter were obtained in the F12 mL/L treatment, with 42.16 cm and 8.42 mm, respectively, while the lowest values were observed in the control treatment, with

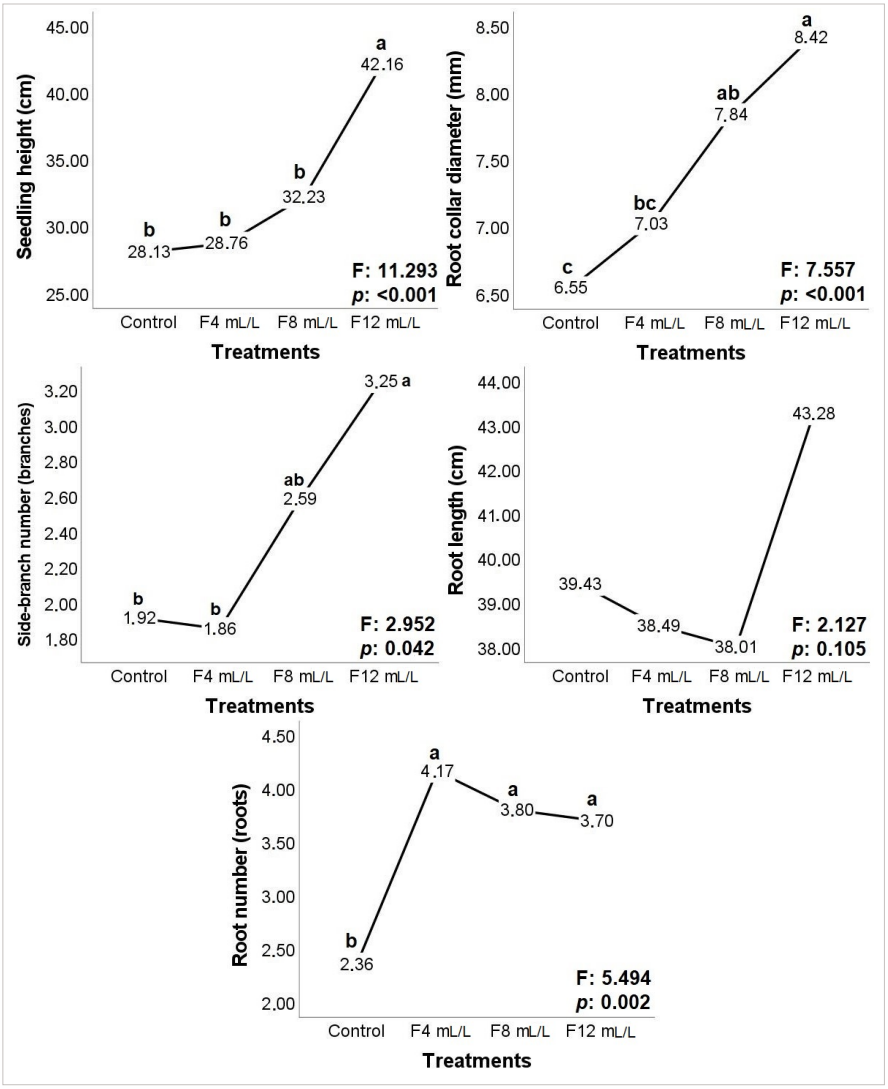

Figure 1. Mean values, ANOVA results, and Duncan's test outcomes for SH, RCD, SBN, RL, and RN

28.13 cm and 6.55 mm, respectively. In terms of these two characteristics, the F8 mL/L treatment (32.23 cm and 7.84 mm) and subsequently the F4 mL/L treatment (28.76 cm and 7.03 mm) showed the next highest values. Additionally, the highest results for the number of side branches, with 3.25 branches, and root length, with 43.28 cm, were also obtained in the F12 mL/L treatment. This was followed by the F8 mL/L treatment with 2.59 branches, the control treatment with 1.92 branches, and the F4 mL/L treatment with 1.86 branches based on the number of side branches. As for root length, the control treatment recorded 39.43 cm, followed by the F4 mL/L treatment with 38.49 cm, and the F8 mL/L treatment with 38.01 cm. In terms of the number of roots, the ranking from highest to lowest was as follows: 4.17 roots in the F4 mL/L treatment, 3.80 roots in the F8 mL/L treatment, 3.70 roots in the F12 mL/L treatment, and 2.36 roots in the control treatment.

As a result of the variance analysis, statistically significant differences were found between treatments at a 99% confidence level in terms of seedling height, root collar diameter, and the number of roots. However, statistically significant differences in the number of lateral branches were observed between treatments options at a 95% confidence level. On the other hand, no significant differences were found between treatments in term of root length. According to the results of Duncan's test, carried out on the morphological characteristics, where statistically significant differences were found, it was determined that two separate groups distinguished according to the height of seedling and the number of roots, three groups according to the number of lateral branches, and four groups according to the diameter of root collar. For seedling height, the F12 mL/L treatment constituted the first group, while the other treatments were grouped together in the second group. Regarding the number of roots, the F4, F8, and F12 mL/L treatments comprised the first group, with the control treatment alone in the last group. As for the groupings related to the number of side branches, the F12 mL/L treatment led the first group, followed by the F8 mL/L treatment in the second group, while the F4 mL/L and control treatments were placed in the third group. For root collar diameter, where each treatment occupied a separate group, the groups were organised in the following order from first to last: F12, F8, F4 mL/L, and the control treatment.

The mean values for fresh and dry weights for shoot, root, and seedling, as well as the results of variance analysis and Duncan's test, are presented in Figure 2.

When examining Figure 2, where all measured weight characteristics are plotted against the treatments, it was noted that the weight values increased as the fertiliser dosage increased from the control treatment to the highest dosage. Accordingly, the highest values for ShFW, ShDW, RFW, RDW, SdFW, and SdDW were obtained in the F12 mL/L treatment, with 15.87 g, 8.58 g, 22.30 g, 11.11 g, 38.18 g, and 19.68 g, respectively. In contrast, the lowest values were recorded in the control treatment, with 5.43 g, 3.50 g, 10.18 g, 5.74 g, 15.61 g, and 9.24 g, respectively. Considering the results of the variance analysis, statistically significant differences were found between treatments at a 99% confidence level for all weight characteristics. According to the results of Duncan's test conduct-

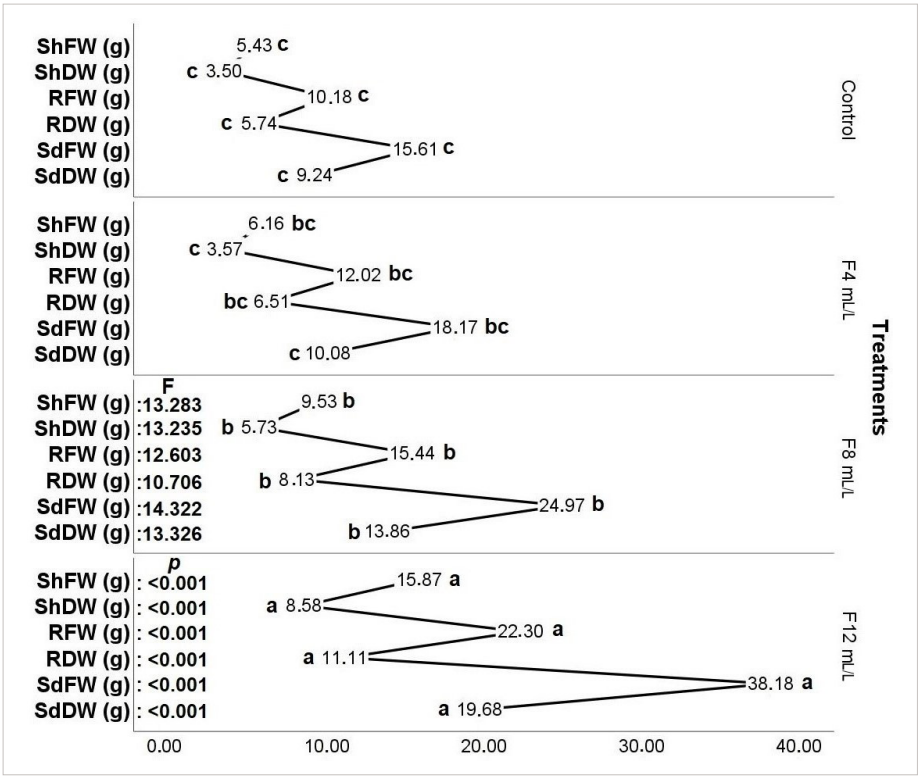

Figure 2. Mean values, ANOVA results, and Duncan's test outcomes for ShFW, ShDW, RFW, RDW, SdFW, and SdDW

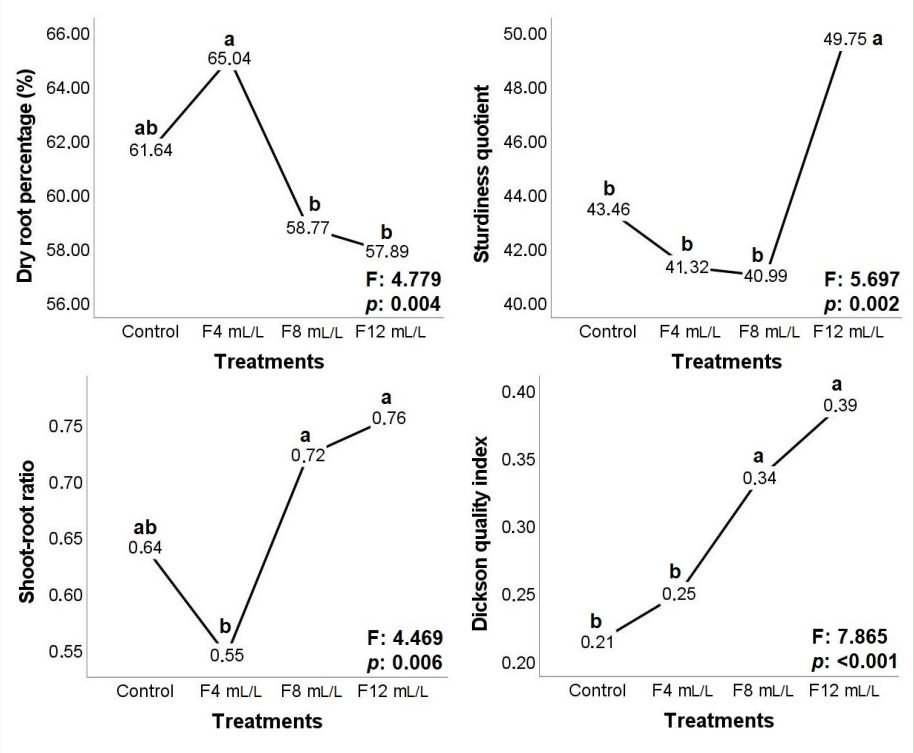

Figure 3. Mean values, ANOVA results, and Duncan's test outcomes for DRP, SQ, S/R, and DQI

ed on all weight characteristics, four distinct groups were identified for ShFW, RFW, RDW, and SdFW, while three groups were observed for ShDW and SdDW. According to the graph in Figure 2, for all weight characteristics, the F12 mL/L treatment formed the first group, the F8 mL/L treatment formed the second group, and the control treatment formed the last group. The F4 mL/L treatment, which formed the third group of four groups identified for ShFW, RFW, RDW, and SdFW, also appeared in the last group of three groups for ShDW and SdDW, again forming the third group. The mean values for dry root percentage, sturdiness quotient, shoot-root ratio, and Dickson quality index, as well as the results of variance analysis and Duncan's test, are presented in Figure 3.

According to Figure 3, the F4 mL/L treatment yielded the highest value for dry root percentage, 65.04%, whilst it resulted in the lowest shoot-root ratio, 0.55. In contrast, the F12 mL/L treatment, which had the lowest percentage of dry roots at 57.89%, recorded the highest shoot-to-root ratio at 0.76. The highest value of the sturdiness quotient was obtained in the F12 mL/L treatment, 49.75, followed by the control treatment, 43.46, the F4 mL/L treatment, 41.32, and the F8 mL/L treatment, 40.99. One of the most comprehensive indices used to evaluate seedling quality based on morphological characteristics is the Dickson quality index, which provides a summary of the traits measured in this study. Accordingly, the F12 mL/L treatment had the highest value, 0.39, while the control treatment had the lowest value, 0.21. For this index, the F8 mL/L treatment gave a value of 0.34, while the F4 mL/L treatment gave a value of 0.25.

The variance analysis results presented in the graphs in Figure 3 revealed statistically significant differences between treatments at a 99% confidence level for dry root percentage, sturdiness quotient, shoot-root ratio, and Dickson quality index. Following the detection of significant differences, the results of Duncan's test showed that three distinct groups were formed for dry root percentage and shoot-root ratio, while two groups were identified for sturdiness quotient and Dickson quality index. The first group, formed by the percentage of dry roots, included the F4 mL/L treatment, the control treatment was in the second group, and the F8 and F12 mL/L treatments were placed in the third group.

According to the resistance coefficient, the first group consisted of the F12 mL/L treatment option, the second group consisted of the control, F4 mL/L and F8 mL/L treatment options.

According to the sturdiness quotient, the first group consisted of the F12 mL/L treatment option, whilst the second group consisted of the control, F4, and F8 mL/L treatment options. Regarding shoot-to-root ratio, the first group included the F8 and F12 mL/L treatments, the second group consisted of the control treatment, and the third and final group was formed by the F4 mL/l treatment. For the Dickson quality index, two groups were formed: the first group included the F8 and F12 mL/L treatments, and the second group comprised the control and F4 mL/L treatments. The percentage distribution of seedling quality based on treatments for sturdiness quotient is shown in Figure 4.

As illustrated in Figure 4, it can be seen that there were no seedlings in the low-quality class for the control treat-

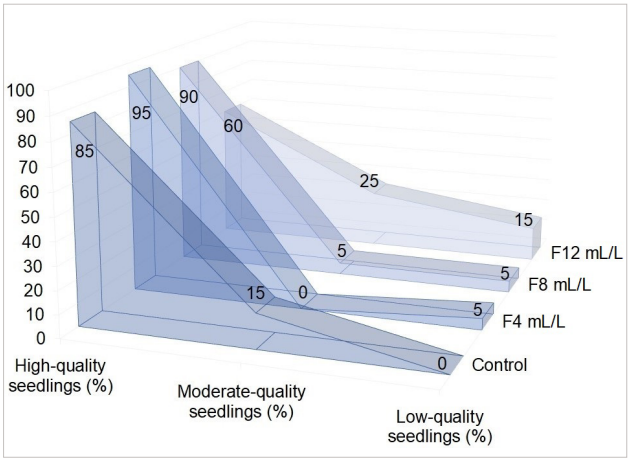

Figure 4. Distribution of treatment options into quality classes based on sturdiness quotient

ment, whilst 5% of the seedlings in the F4 and F8 mL/L treatments, and 15% of the seedlings in the F12 mL/L treatment, fell into this class. In the moderate-quality class, there were no seedlings in the F4 mL/L treatment, while 5% of the seedlings in the F8 mL/L treatment, 15% in the control treatment, and 25% in the F12 mL/L treatment were classified as moderate-quality. The high-quality class comprised 60% of the seedlings in the F12 mL/L treatment, 85% in the control treatment, 90% in the F8 mL/L treatment, and 95% in the F4 mL/L treatment. The obtained values of the Dickson quality index were in the range from 0.00 to 0.70. The graphical representation of the distribution of seedlings by treatment options in successive intervals, together with their percentage equivalents, is presented in Figure 5.

When examining the graph on the left in Figure 5, it was found that the distribution toward the right side of the graph pertains to the control seedlings, and no seedlings with a DQI value in the range of 0.61–0.70 were identified. The downward distribution represents the seedlings in the F4 mL/L treatment, where no seedlings with a DQI greater than 0.50 or less than 0.11 were observed. In the distribution toward the left side of the graph, which corresponds to the F8 mL/L treatment, no seedlings with a DQI below 0.11 were found, whilst in the upward distribution representing the F12 mL/L treatment, no seedlings with a DQI below 0.21 were present.

This observation was indicated in the percentage-based diagram on the right panel of Figure 5, where only seedlings from the control treatment (5%) were found in the lowest range. The DQI ranges where the control seedlings showed the highest distribution were 0.11– 0.20 (30%) and 0.21– 0.30 (30%). The highest distribution range for seedlings treated with F4 mL/L was found to be 0.11–0.20, or 45%. On the other hand, in the highest DQI range (0.61– 0.70), seedlings from the treatments of F8 and F12 mL/L were represented at 5%. However, no seedlings in the 0.11–0.20 range were found in the F12 mL/L treatment, while 15% of the seedlings in the F8 mL/L treatment were within this range. The results of the correlation analysis conducted to determine the direction and strength of the relationships between all morphological characteristics measured and calculated in the study are presented in Figure 6.

According to the results of the correlation analysis, a powerful positive correlation was identified between seedling height and root collar diameter. This relationship indicates that as the seedling height increases, the root collar diameter also increases in parallel. Similarly, seedling height showed positive correlations with all other morphological

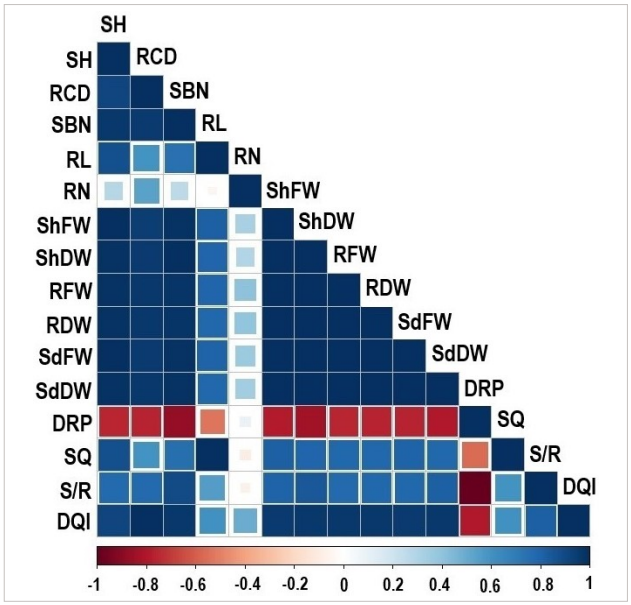

Figure 6. Correlation analysis of morphological characteristics

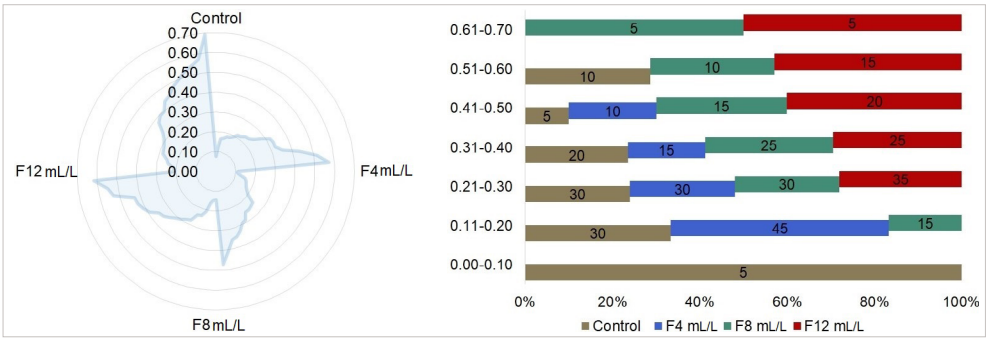

Figure 5. The Dickson quality index values of seedlings by treatment (left panel) and their percentage distribution (right panel)

characteristics except for the dry root percentage. Among them, all correlations, except for the one with the number of roots, were powerful. The correlation relationships described for seedling height were also similarly observed for root collar diameter and side branch number. When examining the correlations related to root length, it was found that, apart from the negative correlations with root number and dry root percentage, there were strong positive correlations with all other characteristics. However, although a negative correlation was determined between root length and root number, it was found to be very weak, indicating that an increase or decrease in root number did not significantly affect root length. The root number stood out as the only characteristic that did not show powerful correlations with the morphological characteristics measured in the study.

While root number exhibited very weak negative correlations with sturdiness quotient and shoot/root ratio, it formed positive correlations with other morphological characteristics. All the weights measured in the study showed powerful positive correlations with each other and with all morphological characteristics except for the dry root percentage. The sturdiness quotient and the shoot/root ratio displayed weak negative correlations with root number and very strong negative correlations with dry root percentage. Except for these two morphological characteristics, they showed strong or very strong correlations with all other characteristics. It was found that the Dickson quality index powerfully positively correlated with all morphological characteristics, except for the percentage of dry roots. The fact that this index showed strong positive correlations with morphological characteristics such as seedling height, root collar diameter, and side branch number, which can be determined without harming the seedlings, is significant for the availability of simple measurements in assessing seedling quality.

Discussion and conclusion

In this study, the one-year-old seedlings of oriental beech were treated with different doses of nanotechnological liquid organomineral fertiliser over one growing season. Following these applications, the development of two-year-old oriental beech seedlings at the end of the second growing season was evaluated based on morphological characteristics and quality indices. The results revealed that this organic-based fertiliser significantly contributed to seedling development. The findings showed that the fertiliser treatments, including F4, F8, and F12 mL/L, resulted in notable increases in almost all morphological characteristics compared to the control. For key morphological traits such as seedling height and root collar diameter, an increasing trend was observed in the data corresponding to higher fertiliser doses starting from the control. Additionally, the highest values for the number of side branches, root length, and root number were observed in the treatments, where fertiliser was applied. Furthermore, the fertiliser treatments stood out in terms of all measured seedling weight characteristics and the Dickson quality index, one of the most comprehensive indices used for evaluating seedling quality.

The study results showed that the F4 mL/L treatment produced the highest root number with 4.17 roots, whilst the F12 mL/L treatment resulted in the highest values for seedling height at 42.16 cm, root collar diameter at 8.42 mm, side-branch number at 3.25 branches, root length at 43.28 cm, shoot fresh weight at 15.87 g, shoot dry weight at 8.58 g, root fresh weight at 22.30 g, root dry weight at 11.11 g, seedling fresh weight at 38.18 g, and seedling dry weight at 19.68 g. In a study determining the pre-planting morphological criteria for oriental beech, it was reported that the minimum required values for two-year-old seedlings are a seedling height of 20–25 cm and a root collar diameter of 5 mm (Özpay and Tosun 1993). Even in the control seedlings, where the lowest values for seedling height (28.13 cm) and root collar diameter (6.55 mm) were recorded, the criteria specified by Özpay and Tosun (1993) were met. In the F12 mL/L treatment, which produced the highest seedling height (42.16 cm) and root collar diameter (8.42 mm), the results significantly exceeded these minimum requirements.

In a study conducted by Güney et al. (2020), the effects of root undercutting, thinning, and fertilisation applications on the morphological characteristics of two-year-old oriental beech seedlings were investigated. The results revealed that the highest seedling height (36.89 cm), side-branch number (2.64 branches), and seedling fresh weight (13.38 g) were observed in seedlings subjected to thinning followed by the application of 50 g/m^2 ammonium nitrate fertiliser. Additionally, while the highest root collar diameter (6.97 mm) was recorded in the root undercutting and thinning treatment, there was no statistically significant difference compared to the fertilisation treatment (6.81 mm). Another study on two-year-old seedlings grown from oriental beech seeds collected from different provenances reported the highest seedling height as 34.60 cm, root collar diameter as 8.27 mm, shoot fresh weight as 10.55 g, root fresh weight as 7.02 g, seedling fresh weight as 17.53 g, shoot dry weight as 6.52 g, root dry weight as 4.27 g, and seedling dry weight as 10.59 g, according to Gülseven et al. (2019). Similarly, Kirdar and Allahverdiev (2003) found that applying Polistimulin-A6 hormone at doses of 50, 100, 150, and 200 mg/L to two-year-old oriental beech seedlings produced the highest seedling height, measured at 52.80 cm, and the largest root collar diameter, reaching 16.40 mm, at the 200 mg/L dose. Additionally, the highest shoot, root, and seedling dry weights were observed at the 150 mg/L dose, measuring 15.00 g, 11.20 g, and 26.20 g, respectively. Similar to this study, results from previous studies also indicate that fertilisation and hormone applications contribute to the development of two-year-old oriental beech seedlings. Moreover, positive effects on the morphological characteristics of oriental beech seedlings have

been reported for practices such as combination with nitrogen-fixing species (Bayraktar and Güney 2022), inoculation with arbuscular mycorrhizal fungi (Özel et al. 2021), application of vermicompost (Atik 2013) and biohumus (Güney et al. 2010). Furthermore, fertilisation applied to a 25-year-old young stand of oriental beech in its natural habitat was also found to enhance the morphological characteristics of the seedlings (Guner et al. 2017).

The highest values for dry root percentage (65.04%) were recorded in the F4 mL/L treatment, while the F12 mL/L treatment produced the highest values for shoot-root ratio (0.76) and Dickson quality index (0.39). In terms of sturdiness quotient, the lowest value indicating the highest quality was observed in the F8 mL/L treatment, with DQI equal to 40.99. For dry root percentage, studies on two-year-old oriental beech seedlings reported values of 56.00% by Güney et al. (2020), 41.31% by Gülseven et al. (2019), and 49.70% by Kirdar and Allahverdiev (2003). Regarding the sturdiness quotient, shoot-root ratio, and Dickson quality index, Güney et al. (2020) obtained values of 42.00, 1.34, and 1.05, respectively, while Gülseven et al. (2019) reported values of 39.94, 1.74, and 0.24, respectively. Compared to the literature, this study achieved higher results for dry root percentage, while sturdiness quotient values were similar. Moreover, considering Jaenicke's (1999) recommendation that shoot-to-root ratio values between ⅟₁ and ½ indicate high-quality seedlings, this study's results are more favourable than those of previous studies. Regarding the Dickson quality index, the values obtained in this study fall within the range of 0.24 to 1.05 reported in earlier studies. However, when morphological characteristics are considered comprehensively, the results of this study stand out with higher values overall.

High dry root percentage (Johnsen et al. 1988, Alım and Kavgacı 2017), a sturdiness quotient below 50 (Aphalo and Rikala 2003, Yahyaoğlu and Genç 2020), a shoot/root ratio between ⅟₁ and ½ (Jaenicke 1999), and a Dickson quality index close to or exceeding 1 (Dickson et al. 1960, Aslan 1986) are indicators of high-quality and healthy seedlings. Considering these parameters as quality criteria, the results of the current study indicate that fertilisation treatments produced higher-quality seedlings compared to the control. Among the fertilisation treatments, F12 mL/L, which achieved the highest values for the Dickson quality index, shoot-root ratio, and several other morphological characteristics, stands out as the treatment that produced the highest-quality seedlings. On the other hand, the occurrence of low-quality individuals in some fertilised treatments may reflect inherent variation among seedlings in nutrient uptake efficiency or physiological responsiveness to the applied doses.

Seedlings in the F12 mL/L treatment had the lowest percentage in the high-quality class for sturdiness quotient, at 60% (Figure 4). However, no seedlings from this treatment were found in the lowest Dickson quality index classes of 0.00–0.10 and 0.11–0.20 (Figure 5). This suggests that the findings applicable to the sturdiness quotient may not necessarily apply to the Dickson quality index. The Dickson quality index, incorporating a greater number of morphological characteristics compared to the sturdiness quotient, calculated using seedling height and root collar diameter, can be considered a better option for achieving more accurate results in seedling quality assessments. Nevertheless, the sturdiness quotient remains a significant factor among morphological characteristics as it allows for a general evaluation without harming the seedling. Indeed, both the sturdiness quotient and the Dickson quality index are frequently used in contemporary studies (Atar and Turna 2018, Banach et al. 2021, Atar et al. 2023, Popović et al. 2024). Furthermore, correlation analysis results from this study revealed that the Dickson quality index exhibited powerful positive correlations with morphological characteristics such as seedling height, root collar diameter, and the number of side branches, all of which can be determined without damaging the seedling, as well as with the sturdiness quotient. Therefore, seedlings with high values for these morphological characteristics and a low sturdiness quotient, particularly below 50, can be considered high-quality and advantageous for planting activities. Notably, the success of planting efforts has been reported to be directly related to the use of high-quality seedlings (Güney et al. 2020).

The significant impact of the fertilisation treatments, which were the most successful in terms of morphological characteristics and seedling quality in this study, can be attributed to the nutrients provided directly to the soil where the seedlings were grown. Fertilisation has been shown in various studies to enhance seedling development, increase resistance to pathogens (Güneş et al. 2007, Esen et al. 2012, Servin et al. 2015), positively affect root development (Singh and Sale 2000, Trubat et al. 2006), and improve drought tolerance in seedlings (Reinbott and Blevins 1999, Trubat et al. 2010). Based on these findings, the fertilisation treatments applied for oriental beech seedlings have demonstrated positive effects on both morphological characteristics and seedling quality. Therefore, the use of fertilisers is recommended for producing high-quality seedlings of the oriental beech. Furthermore, considering the results of this study, there was a parallel increase in morphological characteristics with increasing fertiliser doses. This suggests that future research could focus on examining the effects of higher doses of the nanotechnological liquid organomineral fertiliser used in this study on seedling development and quality. While doing so, to ensure cost-effectiveness and avoid potential nutrient overuse, fertiliser doses should be optimised in future studies based on both seedling performance and economic viability in operational nursery settings.

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