

Article

The Effects of Different Container Types and Substrate Ratios on the Growth Characteristics of *Zelkova schneideriana* Hand.-Mazz. Seedlings

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Abstract

To optimize container seedling cultivation of Chinese zelkova (*Zelkova schneideriana* Hand.-Mazz.), a three-factor completely randomized design was used to systematically evaluate the effects of container material, container size, and substrate composition on seedling growth, physiological traits, and root morphology. Different container materials, three container sizes, and multiple composite substrates were tested. Seedling height, biomass accumulation, photosynthetic characteristics, and root morphological indices were measured, and principal component analysis combined with comprehensive evaluation was applied to identify optimal treatments. The results showed that container size was one of the major factors affecting overall seedling quality, with large containers generally enhancing seedling height, biomass accumulation, photosynthetic capacity, and root development. Among container materials, B-type containers generally exhibited better overall performance under medium- and large-size conditions. Substrate composition showed a significant regulatory effect under appropriate container conditions, and the T₃ composite substrate, composed of yellow soil (40%), peat (10%), sphagnum peat (15%), vermiculite (10%), rice husk (15%), and corn cob (10%), achieved the highest comprehensive score. According to the PCA-based comprehensive evaluation, the T₃/A₃ treatment ranked first, followed by T₃/B₂. Overall, the combination of B-type containers, appropriate medium-to-large container size, and the T₃ substrate showed superior nursery performance. In particular, T₃/A₃ ranked first in the comprehensive evaluation, followed by T₃/B₂, indicating that both large black plastic containers and medium-sized B-type containers performed well under the T₃ substrate.



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1. Introduction

Chinese zelkova (*Zelkova schneideriana* Hand.-Mazz.), belonging to the family Ulmaceae and the genus *Zelkova*, is one of the rare and endemic broad-leaved tree species in China, widely distributed across Central China, East China, and parts of Southwest China [1,2].

This species is characterized by a stately growth form and pronounced seasonal variation in leaf coloration, conferring both high ornamental value and important ecological functions [3]. Its wood is hard, fine-grained, and highly resistant to decay, making it an important timber resource for high-grade furniture, construction, and landscape engineering [4]. In recent years, the wild populations of *Z. schneideriana* have declined continuously due to habitat fragmentation [5], intensified human disturbance, and limited natural regeneration capacity. Consequently, it has been listed as a Class II species in the National Key Protected Wild Plant List of China, highlighting the urgent need for effective conservation and sustainable utilization through artificial propagation and large-scale cultivation.

Container seedling cultivation has become an important technical approach for the artificial propagation of rare and native tree species owing to its advantages in root control and stimulation [6], precise water and nutrient management, and stable seedling quality. Compared with traditional bare-root seedlings [7], container-grown seedlings exhibit more intact root systems, shorter transplant shock periods, and higher survival rates after outplanting, making them particularly suitable for sites with complex environmental conditions or urgent ecological restoration demands [8]. Within container-based nursery systems, container type and substrate composition are key determinants of seedling quality [9]. The material, structure, and size of containers directly influence root spatial distribution, aeration and drainage conditions, and root architecture, while the physicochemical properties of substrates regulate water retention, aeration, and nutrient supply, thereby affecting seedling growth performance and physiological functioning.

Previous studies have demonstrated that different container types and substrate compositions exert significant effects on seedling growth. For example, appropriate pore structure can promote root extension [10] and improve water and nutrient use efficiency [11], while composite substrates rich in organic matter and with good aeration are conducive to root development and enhanced photosynthetic capacity [12,13]. However, most existing studies have focused on the effects of single factors, such as substrate composition or container size, whereas systematic investigations into the interactive effects of container type, container size, and substrate composition remain limited [14,15]. In particular, research on *Z. schneideriana* nursery practices has largely emphasized morphological traits such as seedling height and ground diameter, with relatively little attention paid to quantitative assessments of root morphology, physiological traits, and overall nursery performance [16–18].

Moreover, in practical production, the criteria for defining an “optimal treatment” vary depending on nursery objectives [19]. When rapid seedling production is prioritized, greater emphasis is placed on aboveground biomass accumulation and photosynthetic capacity; in contrast, when improving transplant survival is the primary goal, root system development and nutrient accumulation become more critical [20]. Therefore, a comprehensive, multi-indicator evaluation of the nursery performance of different container–substrate combinations is essential for establishing a scientific and widely applicable container seedling cultivation system for *Z. schneideriana*.

Based on these considerations, the present study investigated *Z. schneideriana* seedlings under different combinations of container type, container size, and substrate composition. Compared with previous studies focusing mainly on container size and substrate ratio [21], the present study further incorporated different container types and systematically analyzed the effects of these treatments on emergence rate, growth traits, physiological characteristics, root morphology, and nutrient accumulation. In addition, principal component analysis was employed to comprehensively evaluate the nursery performance of different treatments [22]. The objectives were to identify optimal container seedling cultivation schemes for *Z. schneideriana* and to provide a scientific basis and technical support for large-scale seedling production and ecological restoration projects in southern China [23].

2. Materials and Methods

2.1. Study Site

The experiment was conducted at the nursery base of Tongxing Forestry Co., Ltd., in Chaling County, Zhuzhou City, Hunan Province, China (26°59′ N, 113°54′ E). The study area is located in a humid subtropical monsoon climate zone, characterized by synchronous rainfall and heat and distinct seasonal variation. The long-term mean annual precipitation ranges from 1300 to 1500 mm, with most rainfall occurring from April to August. The long-term mean annual temperature is approximately 17.8 °C, and the average annual relative humidity is about 75%. These environmental conditions are suitable for the cultivation of container seedlings of *Zelkova schneideriana* Hand.-Mazz.

2.2. Experimental Materials

Seeds used in this study were collected in mid-November 2023 from mature mother trees of *Zelkova schneideriana* in the Qingshigang State-owned Forest Farm, Yanling County, Zhuzhou City, Hunan Province, China. The forest farm is located approximately within 26°06′45″–27°07′56″ N and 113°33′51″–114°07′07″ E, and the collection site was at an elevation of about 2000 m. After collection, the seeds were air-dried under shade conditions. Damaged, shriveled, and mechanically injured seeds were removed, and seeds with uniform size and good plumpness were selected for the experiment. The selected seeds were stored at 4 °C until sowing. Sowing was carried out in early April 2024.

The substrates were prepared from yellow soil, peat soil, grass peat, perlite, vermiculite, rice husk, and sawdust according to the volumetric ratios shown in Table 1. Three types of containers were used, namely black plastic pots, bicolor nursery pots, and nonwoven fabric bags. Three size classes were established for each container type, and the detailed specifications are listed in Table 2.

Table 1. Composition and physicochemical properties of the substrate treatments used in this study.

Substrate	Yellow Soil (%)	Peat (%)	Sphagnum Peat (%)	Vermiculite (%)	Perlite (%)	Rice Husk (%)	Sawdust (%)	Corn Cob (%)
CK	100	0	0	0	0	0	0	0
T1	50	5	5	0	5	5	30	0
T2	50	20	10	5	0	10	5	0
T3	40	10	15	10	0	15	0	10
T4	40	0	20	0	10	10	0	20
T5	30	20	0	0	20	20	0	10

CK indicates the control treatment. All substrate components were mixed on a volume basis.

Table 2. Various container specification scenarios.

Container Material	Specification (Diameter × Height, cm)		
Black plastic pot	A ₁ (13 × 13)	A ₂ (18 × 18)	A ₃ (23 × 23)
Bicolor nursery pot	B ₁ (13 × 13)	B ₂ (18 × 18)	B ₃ (23 × 23)
Non-woven fabric bag	C ₁ (13 × 13)	C ₂ (18 × 18)	C ₃ (23 × 23)

The nursery was equipped with an automatic sprinkler irrigation system with mist nozzles. During cultivation, all treatments were managed uniformly according to weather conditions and substrate moisture status. Under normal conditions, irrigation was applied every 3–5 days, and the irrigation frequency was appropriately increased during periods of high summer temperature.

2.3. Experimental Design

A three-factor completely randomized design was used in this study, with container type, container size, and substrate composition as the experimental factors. Five substrate treatments (CK and T₁–T₅, as applicable in the tables and figures) were established according to volumetric mixing ratios, and their compositions are listed in Table 1. The container treatments included three container types, each with three size classes, resulting in nine container treatments in total (Table 2).

The substrate and container treatments were combined factorially to generate all treatment combinations. Each treatment was replicated three times, and 10 seedlings were measured in each replicate. Therefore, 30 seedlings were used for each treatment in growth-related measurements. All treatments were randomly arranged within the nursery area and maintained under the same routine nursery management conditions.

The substrate treatments (T₁–T₅) were established on the basis of combining yellow soil with different proportions of locally available organic and inorganic amendments, including peat, sphagnum peat, vermiculite, perlite, rice husk, sawdust, and corn cob. The purpose of this design was to construct substrate formulations with contrasting structural and nutritional properties, so as to compare their suitability for container seedling cultivation of *Zelkova schneideriana*. Rather than representing arbitrary mixtures, the T₁–T₅ treatments were selected to form a gradient of substrate composition and practical nursery options under local material conditions.

2.4. Determination of Physicochemical Properties of Substrates

Before sowing, the physicochemical properties of each substrate treatment were determined. After thorough mixing, each substrate was homogenized and subsampled using the quartering method. For each substrate treatment, three samples were used for the determination of physical and chemical properties.

The physical properties measured included bulk density, capillary porosity, non-capillary porosity, and total porosity. Bulk density was determined using the core method, and the porosity indices were calculated based on substrate water content under saturated water absorption and free drainage conditions [24].

The chemical properties included total nitrogen, total phosphorus, and total potassium. Total nitrogen was determined using the Kjeldahl method [25], total phosphorus was measured using the molybdenum–antimony colorimetric method [26], and total potassium was determined by flame photometry [27]. Mean values for the three samples from each substrate type were used for subsequent analysis.

2.5. Measurement of Growth Parameters

From July to October 2024, the growth performance of the seedlings under different treatments was monitored. During the experimental period, emergence rate was recorded at 40-day intervals. For growth-related measurements, each treatment included three replicates, and 10 seedlings were measured in each replicate, giving a total of 30 seedlings per treatment. Seedling height was measured using a steel ruler with an accuracy of 0.01 cm, and ground diameter was measured using a digital vernier caliper with an accuracy of 0.01 mm.

At the end of the experiment, one representative seedling was selected from each replicate based on the mean values of seedling height and ground diameter. These representative seedlings were used for subsequent measurements of root morphology, dry mass, and physiological traits. Statistical analysis was conducted using the mean values for each of the three replicates, and the results are presented as mean $\pm$ standard error (SE).

After sampling, the roots were carefully washed with clean water to remove adhering substrate, and excess surface moisture was gently removed. Each seedling was then

separated into roots, stems, and leaves at the root collar. Root systems were scanned and analyzed using WinRHIZO Pro software (v2004b; Regent Instruments Inc., Quebec, QC, Canada), and root morphological parameters, including total root length, root surface area, root volume, root tip number, and mean root diameter, were quantified accordingly [28].

The separated roots, stems, and leaves were placed in paper bags and heated at 120 °C for 10 min to deactivate enzymes, followed by oven drying at 60 °C to constant weight [29]. Dry mass was determined using an analytical balance with a precision of 0.001 g.

Emergence rate (%) was calculated as follows:

$$\text{Emergence rate (\%)} = (\text{Number of visible seedlings} / \text{Number of sown seeds}) \times 100.$$

2.6. Measurement of Physiological Parameters

In early October 2024, photosynthetic parameters were measured on clear and windless mornings between 08:30 and 11:30. Fully expanded, mature, and healthy functional leaves were selected from representative seedlings in each treatment. For each treatment, one representative seedling was selected from each of the three replicates, and the mean value of the three replicates was used for statistical analysis. Gas-exchange measurements were conducted using a portable photosynthesis system (LI-6400XT, LI-COR Biosciences, Lincoln, NE, USA) [30,31]. During measurement, photosynthetically active radiation was set to 1200 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$, the reference CO_2 concentration was set to 400 $\mu\text{mol}\cdot\text{mol}^{-1}$, the leaf chamber temperature was maintained at 28 °C, and the relative air humidity was controlled at approximately 65%. For each leaf, values were recorded only after the readings had stabilized. Net photosynthetic rate (P_n), transpiration rate (T_r), stomatal conductance (G_s), and intercellular CO_2 concentration (C_i) were then recorded.

Chlorophyll content was determined using the 80% acetone extraction method [32]. Mature leaves from three biological replicates of each treatment were collected for analysis. Leaf nutrient contents were determined as follows: total nitrogen was measured using the Kjeldahl method [25], total phosphorus was determined using the molybdenum–antimony colorimetric method [33], and total potassium was measured by flame photometry [34]. All physiological and nutrient measurements were performed with three replicates for each treatment, and the results are presented as mean $\pm$ standard error (SE).

2.7. Data Analysis

All measured data were compiled and preliminarily processed using WPS Excel 2020 (Kingsoft Office Software Corporation Ltd., Beijing, China). Statistical analyses were conducted using IBM SPSS Statistics 27.0 (IBM Corp., Armonk, NY, USA). Analysis of variance (ANOVA) was used to evaluate the effects of container type, container size, substrate composition, and their interactions. To further clarify the factor-level effects in this three-factor experiment, three-way ANOVA was conducted for the major growth and physiological traits, with substrate composition, container type, and container size treated as fixed factors. When significant effects or interactions were detected, Tukey's multiple comparison test was used for post hoc comparisons at the 0.05 significance level. For grouped figures, comparisons were performed among substrate treatments within each container treatment, whereas for tables, lowercase letters within the same column indicate significant differences among the listed treatment combinations. In all cases, the mean value for each replicate was used for statistical analysis, and the results are presented as mean $\pm$ standard error (SE). Figures and tables were prepared using Origin 2024 (OriginLab Corporation, Northampton, MA, USA).

In addition, principal component analysis (PCA) was employed to reduce data dimensionality and to comprehensively evaluate multiple indicators of growth and physiolog-

ical performance in container-grown seedlings, with the aim of identifying the optimal substrate–container combinations based on overall seedling performance.

3. Results

To clarify the factor-level statistical effects in this three-factor experiment, a three-way ANOVA was performed for the major growth and physiological traits of *Zelkova schneideriana* Hand.-Mazz. seedlings, and the results are summarized in Table 3. Overall, substrate composition, container type, and container size exerted varying degrees of influence on the measured traits, and several interaction effects were also significant, indicating that seedling performance was jointly regulated by these experimental factors rather than by any single factor alone.

Table 3. Summary of three-way ANOVA results for the major growth and physiological traits of *Zelkova schneideriana* Hand.-Mazz. seedlings under different substrate–container treatments.

Trait	Substrate Composition (S)	Container Type (C)	Container Size (Z)	S × C	S × Z	C × Z	S × C × Z
Seedling height	$F = 350.93$, $p < 0.001$	$F = 2.21$, $p = 0.111$	$F = 30.02$, $p < 0.001$	$F = 9.46$, $p < 0.001$	$F = 2.42$, $p = 0.008$	$F = 10.25$, $p < 0.001$	$F = 3.58$, $p < 0.001$
Ground diameter	$F = 104.69$, $p < 0.001$	$F = 5.58$, $p = 0.004$	$F = 18.31$, $p < 0.001$	$F = 2.16$, $p = 0.019$	$F = 1.14$, $p = 0.330$	$F = 6.78$, $p < 0.001$	$F = 3.41$, $p < 0.001$
Aboveground dry mass	$F = 6980.16$, $p < 0.001$	$F = 50.84$, $p < 0.001$	$F = 677.04$, $p < 0.001$	$F = 84.23$, $p < 0.001$	$F = 38.43$, $p < 0.001$	$F = 165.91$, $p < 0.001$	$F = 51.48$, $p < 0.001$
Belowground dry mass	$F = 10,135.26$, $p < 0.001$	$F = 48.04$, $p < 0.001$	$F = 1393.89$, $p < 0.001$	$F = 151.37$, $p < 0.001$	$F = 163.26$, $p < 0.001$	$F = 259.55$, $p < 0.001$	$F = 161.39$, $p < 0.001$
Chlorophyll content	$F = 4243.95$, $p < 0.001$	$F = 568.85$, $p < 0.001$	$F = 1761.21$, $p < 0.001$	$F = 139.39$, $p < 0.001$	$F = 93.78$, $p < 0.001$	$F = 863.62$, $p < 0.001$	$F = 279.94$, $p < 0.001$
N content	$F = 1020.31$, $p < 0.001$	$F = 97.01$, $p < 0.001$	$F = 66.13$, $p < 0.001$	$F = 68.11$, $p < 0.001$	$F = 57.09$, $p < 0.001$	$F = 26.65$, $p < 0.001$	$F = 28.36$, $p < 0.001$
P content	$F = 2923.50$, $p < 0.001$	$F = 132.10$, $p < 0.001$	$F = 189.73$, $p < 0.001$	$F = 94.78$, $p < 0.001$	$F = 76.71$, $p < 0.001$	$F = 55.08$, $p < 0.001$	$F = 52.84$, $p < 0.001$
K content	$F = 1520.25$, $p < 0.001$	$F = 54.04$, $p < 0.001$	$F = 90.78$, $p < 0.001$	$F = 66.09$, $p < 0.001$	$F = 74.66$, $p < 0.001$	$F = 51.58$, $p < 0.001$	$F = 51.24$, $p < 0.001$

S, substrate composition; C, container type; Z, container size. Values are presented as F and p values from three-way ANOVA, with substrate composition, container type, and container size treated as fixed factors.

As shown in Table 3, three-way ANOVA indicated that substrate composition and container size significantly affected all measured traits, whereas the effect of container type differed among traits. Specifically, container type had no significant main effect on seedling height, but significantly affected ground diameter, dry mass accumulation, chlorophyll content, and nutrient contents. These results suggest that substrate composition and container size were more consistent determinants of seedling performance, whereas the influence of container type was more trait-dependent.

In addition, significant two-way and three-way interaction effects were detected for most traits, indicating that the influence of each experimental factor could not be interpreted independently. Instead, the effects of substrate composition, container type, and container size were interconnected, and the growth responses of *Zelkova schneideriana* Hand.-Mazz. seedlings were jointly shaped by these combined factors.

3.1. Physicochemical Properties of Substrates

Significant differences in nutrient contents and physical structural characteristics were observed among the different substrate treatments (Table 4). Overall, compared with the conventional control substrate (CK), all lightweight composite substrates exhibited varying degrees of improvement in nutrient supply capacity and pore structure, indicating that substrate formulation optimization can effectively enhance the physicochemical properties of substrates used in container seedling cultivation.

Table 4. Physicochemical properties of different substrate treatments.

Substrate Type	Total P (mg·g ⁻¹)	K Content (%)	Bulk Density (g·cm ⁻³)	Non-Capillary Porosity (%)	Capillary Porosity (%)	Total Porosity (%)	Total Nitrogen (g·kg ⁻¹)
CK	0.29 ± 0.02c	1.67 ± 0.15bc	1.27 ± 0.11a	3.62 ± 0.43c	22.85 ± 1.91d	26.47 ± 2.66d	0.63 ± 0.04d
T ₁	0.47 ± 0.03b	1.45 ± 0.13d	1.29 ± 0.13a	3.02 ± 0.39c	24.52 ± 2.32bc	27.54 ± 2.87cd	1.34 ± 0.13b
T ₂	0.42 ± 0.02b	1.48 ± 0.15d	1.04 ± 0.14c	5.02 ± 0.38b	24.08 ± 1.83bc	29.10 ± 2.64bc	1.59 ± 0.11b
T ₃	0.92 ± 0.05a	1.71 ± 0.17ab	1.09 ± 0.12c	6.02 ± 0.48a	28.52 ± 2.54a	34.54 ± 3.64a	2.41 ± 0.23a
T ₄	0.39 ± 0.02b	1.68 ± 0.14bc	1.16 ± 0.13b	2.02 ± 0.33c	28.07 ± 2.46a	30.09 ± 3.48bc	1.52 ± 0.13b
T ₅	0.44 ± 0.03b	1.57 ± 0.13cd	1.27 ± 0.11a	3.02 ± 0.40c	23.93 ± 2.21cd	26.95 ± 2.59d	0.91 ± 0.07c

Values are presented as mean ± SE ($n = 3$). Different lowercase letters indicate significant differences among treatments according to the Tukey multiple comparison test at $p < 0.05$. CK indicates the control treatment.

Regarding nutrient contents, total phosphorus and soil total nitrogen showed pronounced differences among treatments. The total phosphorus content of CK was the lowest (0.291 mg·g⁻¹), whereas T₃ exhibited the highest value (0.921 mg·g⁻¹), approximately 3.16 times that of CK, indicating a markedly stronger phosphorus supply capacity. The total phosphorus contents of T₁, T₂, T₄, and T₅ were all higher than that of CK but lower than that of T₃. A similar trend was observed for soil total nitrogen. T₃ had the highest total nitrogen content (2.414 g·kg⁻¹), which was significantly greater than those of the other treatments, while CK showed the lowest value (0.633 g·kg⁻¹), demonstrating that lightweight composite substrates effectively enhanced nitrogen availability.

Potassium content varied only slightly among treatments, ranging from 1.449% to 1.713%. T₃ exhibited a slightly higher potassium content, whereas T₁ showed a relatively lower value. Overall, the differences were limited, suggesting that potassium availability was relatively stable among substrates and was not a primary limiting factor distinguishing substrate performance under the present experimental conditions.

In terms of physical properties, substrate bulk density and pore structure differed markedly among treatments. CK as well as T₁ and T₅ exhibited relatively high bulk densities (1.267–1.294 g·cm⁻³), whereas T₂ and T₃ showed significantly reduced bulk densities, with T₂ being the lowest (1.044 g·cm⁻³), indicating that the incorporation of lightweight materials effectively reduced substrate compaction. Pore structure analysis revealed that T₃ exhibited the highest non-capillary porosity (6.020%), capillary porosity (28.518%), and total porosity (34.538%) among all treatments, which were markedly higher than those of CK (26.466%). This indicates a favorable balance between aeration and water-holding capacity. The total porosity of T₂ and T₄ was also higher than that of CK, reaching 29.101% and 30.094%, respectively, reflecting improved structural properties.

Overall, substantial differences in nutrient supply capacity and pore structure were observed among the substrate formulations. Among them, T₃ showed clear advantages in both nitrogen and phosphorus availability as well as pore structure optimization, combining relatively low bulk density with high total porosity. These characteristics provide a favorable physicochemical foundation for root development and water–air regulation in container-grown *Zelkova schneideriana* seedlings. T₂ and T₄ also performed well in reducing bulk density and improving pore structure, whereas CK was comparatively inferior in both nutrient availability and physical structure.

3.2. Effects of Different Container–Substrate Treatments on Seedling Emergence Rate

Under different container–substrate treatments, the emergence rate of *Zelkova schneideriana* seeds remained generally high (Table 5). Emergence rates ranged from 96% to 100% across all treatments, with most treatments exceeding 98% and several reaching 100%. These results indicate that *Z. schneideriana* seeds exhibit strong germination capacity under the experimental conditions and show good adaptability to different substrate formulations and container configurations.

Table 5. Emergence rate of *Zelkova schneideriana* Hand.-Mazz. under different substrate–container combinations.

Substrate– Container Combination	Emergence Rate (%)	Substrate– Container Combination	Emergence Rate (%)	Substrate– Container Combination	Emergence Rate (%)
CK/A ₁	96.12 ± 3.48bc	T ₂ /A ₁	100.00 ± 0.00a	T ₄ /A ₁	99.23 ± 0.89a
CK/A ₂	98.38 ± 3.94ab	T ₂ /A ₂	98.38 ± 1.83ab	T ₄ /A ₂	98.23 ± 1.48ab
CK/A ₃	97.19 ± 3.99b	T ₂ /A ₃	96.94 ± 2.31bc	T ₄ /A ₃	99.47 ± 1.34a
CK/B ₁	99.33 ± 2.32a	T ₂ /B ₁	97.47 ± 2.93b	T ₄ /B ₁	96.25 ± 2.52bc
CK/B ₂	100.00 ± 0.00a	T ₂ /B ₂	100.00 ± 0.00a	T ₄ /B ₂	100.00 ± 0.00a
CK/B ₃	98.47 ± 3.29ab	T ₂ /B ₃	99.48 ± 1.23a	T ₄ /B ₃	99.54 ± 1.97a
CK/C ₁	96.37 ± 2.18bc	T ₂ /C ₁	98.29 ± 2.41ab	T ₄ /C ₁	100.00 ± 0.00a
CK/C ₂	100.00 ± 0.00a	T ₂ /C ₂	99.85 ± 1.49a	T ₄ /C ₂	98.55 ± 1.57ab
CK/C ₃	99.48 ± 2.11a	T ₂ /C ₃	100.00 ± 0.00a	T ₄ /C ₃	99.47 ± 2.34a
T ₁ /A ₁	98.78 ± 2.94ab	T ₃ /A ₁	100.00 ± 0.00a	T ₅ /A ₁	96.34 ± 2.73bc
T ₁ /A ₂	100.00 ± 0.00a	T ₃ /A ₂	100.00 ± 0.00a	T ₅ /A ₂	100.00 ± 0.00a
T ₁ /A ₃	99.64 ± 2.81a	T ₃ /A ₃	99.59 ± 1.49a	T ₅ /A ₃	99.46 ± 1.38a
T ₁ /B ₁	100.00 ± 0.00a	T ₃ /B ₁	99.82 ± 1.03a	T ₅ /B ₁	98.78 ± 3.87ab
T ₁ /B ₂	100.00 ± 0.00a	T ₃ /B ₂	98.36 ± 2.46ab	T ₅ /B ₂	100.00 ± 0.00a
T ₁ /B ₃	100.00 ± 0.00a	T ₃ /B ₃	96.21 ± 2.11bc	T ₅ /B ₃	100.00 ± 0.00a
T ₁ /C ₁	98.84 ± 2.11ab	T ₃ /C ₁	97.32 ± 1.23b	T ₅ /C ₁	97.96 ± 3.25b
T ₁ /C ₂	99.84 ± 1.38a	T ₃ /C ₂	99.39 ± 1.12a	T ₅ /C ₂	98.74 ± 2.73ab
T ₁ /C ₃	100.00 ± 0.00a	T ₃ /C ₃	100.00 ± 0.00a	T ₅ /C ₃	97.73 ± 2.16b

Values are presented as mean ± SE ($n = 3$). Different lowercase letters within the same column indicate significant differences among the listed substrate–container treatment combinations according to Tukey’s multiple comparison test at $p < 0.05$. CK indicates the control substrate treatment; T₁–T₅ represent different substrate treatments, and A₁–C₃ represent different container treatments.

From the perspective of substrate effects, differences in emergence rate among substrate treatments were relatively small under various container conditions. Neither the control substrate (CK) nor the lightweight composite substrates (T₁–T₅) showed any obvious inhibitory effects on seed emergence, suggesting that all substrate formulations were able to meet the basic requirements for water availability and aeration during the germination stage. Overall, emergence rate was not a key indicator for distinguishing the performance of different substrate treatments.

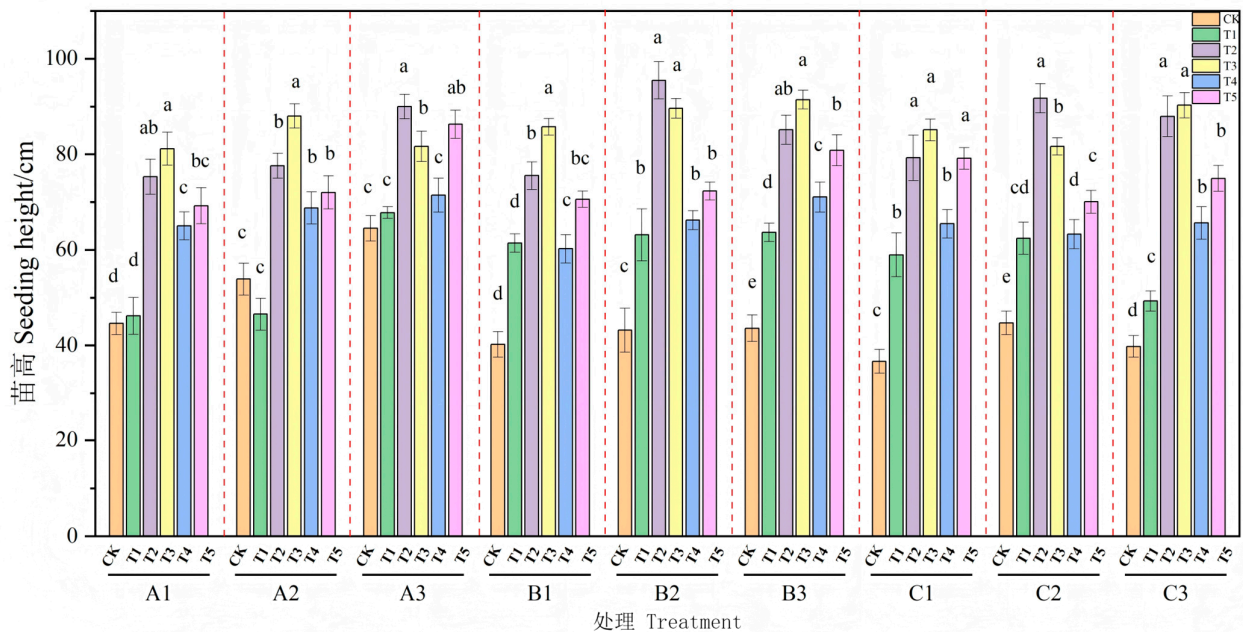
With respect to container effects, different container materials and sizes had limited influence on emergence rate; however, some differences in stability were observed. Compared with small containers (13 cm × 13 cm), medium and large containers (18 × 18 cm and 23 × 23 cm) generally exhibited slightly higher and more stable emergence rates, with most treatments reaching 98%–100%. This suggests that larger container volumes may buffer fluctuations in substrate moisture and temperature, thereby providing a more stable microenvironment for seed germination. No clear differences in emergence rate were observed among container materials, indicating that bicolor rigid pots, black plastic pots, and nonwoven fabric containers were all suitable during the germination stage.

Overall, the effects of different container–substrate treatments on the emergence rate of *Z. schneideriana* were relatively minor, and all treatments ensured a high level of seedling emergence. These results suggest that, under the present experimental conditions, container and substrate configurations exerted limited constraints during the germination stage. Consequently, a relatively uniform initial seedling establishment was achieved, providing a consistent foundation for subsequent differences in vegetative growth, biomass accumulation, and root morphological development.

3.3. Effects of Different Container–Substrate Treatments on Vegetative Growth of *Zelkova schneideriana*

Significant differences in vegetative growth of container-grown *Zelkova schneideriana* seedlings were observed among treatments, mainly reflected by variations in seedling height and ground diameter (Figure 1). Overall, similar trends were observed for both traits across treatments; however, differences in growth level were more pronounced under different container conditions.

(A) Seedling height/cm



(B) Ground diameter/mm

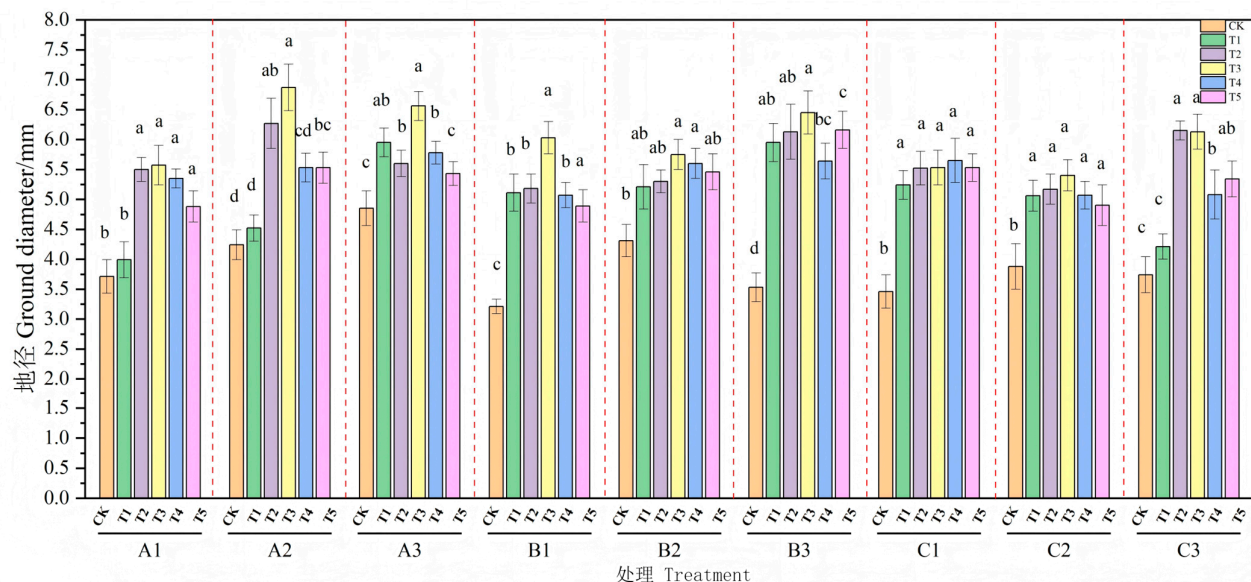


Figure 1. Seedling height (A) and ground diameter (B) of *Zelkova schneideriana* Hand.-Mazz. under different substrate-container treatments. Values are presented as mean $\pm$ SE ($n = 3$). Within each container treatment (A_1 – C_3), different lowercase letters indicate significant differences among substrate treatments (CK and T_1 – T_5) according to Tukey's multiple comparison test at $p < 0.05$. CK indicates the control substrate treatment; T_1 – T_5 represent different substrate treatments, and A_1 – C_3 represent different container treatments.

From the perspective of container effects, under identical substrate conditions, container size showed a clear influence on seedling height and ground diameter. As container size increased from small (13 cm × 13 cm) to medium and large sizes (18 cm × 18 cm and 23 cm × 23 cm), both seedling height and ground diameter generally showed an increasing trend. Seedlings grown in A₂ and A₃, B₂ and B₃, as well as C₂ and C₃ treatments generally exhibited higher values of seedling height and ground diameter, whereas vegetative growth was relatively restricted in A₁, B₁, and C₁ treatments. These results suggest that limited container volume may restrict vegetative growth to some extent. Differences among container materials were also observed, with B-type containers under medium and large sizes generally showing greater seedling height and ground diameter, suggesting a relatively stronger growth-promoting tendency.

Based on the evident effects of container size and material, differences in vegetative growth among substrate treatments were further compared. Under the same container conditions, seedling height and ground diameter in all lightweight composite substrate treatments were generally higher than those in the control substrate (CK), indicating that substrate formulation played an important regulatory role in vegetative growth. Among the substrates, T₃ consistently resulted in the highest or second-highest seedling height and ground diameter under most container conditions, showing a relatively stable growth-promoting effect. T₂ and T₄ ranked next, whereas the effects of T₁ and T₅ were comparatively weaker, although they still generally performed better than CK. Differences among substrate treatments were more pronounced in medium and large containers, while such differences were relatively reduced in small containers.

These results indicate that container size was an important structural factor affecting the vegetative growth of *Z. schneideriana* container seedlings. Differences among container materials were also observed, with B-type containers under medium and large sizes generally showing relatively better vegetative growth performance.

3.4. Effects of Different Container–Substrate Treatments on Aboveground and Belowground Dry Mass of *Zelkova schneideriana*

Significant differences in aboveground and belowground dry mass of container-grown *Zelkova schneideriana* seedlings were observed among treatments (Table 6). Overall, similar variation patterns were found for aboveground and belowground dry mass across treatments. Three-way ANOVA showed that substrate composition, container type, and container size all significantly affected aboveground and belowground dry mass (Table 3). In general, seedlings grown in lightweight composite substrates tended to exhibit greater dry mass accumulation than those grown in the control substrate (CK), although the magnitude of this effect varied with container type and container size.

From the perspective of container effects, under identical substrate conditions, container size had a significant influence on both aboveground and belowground dry mass. As container size increased from small (13 cm × 13 cm) to medium and large sizes (18 cm × 18 cm and 23 cm × 23 cm), aboveground and belowground dry mass showed a clear increasing trend. Higher levels of dry matter accumulation were generally observed in A₂ and A₃, B₂ and B₃, as well as C₂ and C₃ treatments, whereas relatively lower values were found in A₁, B₁, and C₁ treatments. These results indicate that container volume imposes a pronounced limitation on dry matter formation. Differences among container materials were also detected, with B-type containers under medium and large sizes showing comparatively higher aboveground and belowground dry mass, reflecting a stronger promoting effect on biomass accumulation.

Table 6. Aboveground and belowground dry mass of *Zelkova schneideriana* Hand.-Mazz. seedlings under different substrate–container treatments.

Substrate– Container Combination	Aboveground DM (g)	Belowground DM (g)	Substrate– Container Combination	Aboveground DM (g)	Belowground DM (g)
CK/A ₁	10.48 ± 0.52d	0.31 ± 0.01b	T ₁ /A ₁	12.63 ± 0.55g	0.43 ± 0.01h
CK/A ₂	15.73 ± 0.35b	0.52 ± 0.01d	T ₁ /A ₂	13.81 ± 0.25fg	0.46 ± 0.01gh
CK/A ₃	23.90 ± 0.42a	0.92 ± 0.01a	T ₁ /A ₃	27.65 ± 0.53a	1.18 ± 0.01a
CK/B ₁	7.35 ± 0.57ef	0.22 ± 0.01f	T ₁ /B ₁	18.49 ± 0.59d	0.66 ± 0.01e
CK/B ₂	8.35 ± 0.57e	0.23 ± 0.01f	T ₁ /B ₂	20.24 ± 0.62c	0.76 ± 0.01c
CK/B ₃	9.91 ± 0.32d	0.26 ± 0.01e	T ₁ /B ₃	22.52 ± 0.60be	0.85 ± 0.01b
CK/C ₁	5.38 ± 0.55g	0.14 ± 0.01h	T ₁ /C ₁	16.47 ± 0.59cd	0.55 ± 0.01f
CK/C ₂	11.70 ± 0.33c	0.35 ± 0.01c	T ₁ /C ₂	19.73 ± 0.56f	0.72 ± 0.01d
CK/C ₃	6.94 ± 0.24f	0.18 ± 0.01g	T ₁ /C ₃	14.69 ± 0.73	0.48 ± 0.01g
T ₂ /A ₁	37.35 ± 0.57f	1.56 ± 0.01g	T ₃ /A ₁	41.82 ± 0.28f	1.82 ± 0.01g
T ₂ /A ₂	39.71 ± 0.34e	1.63 ± 0.01fg	T ₃ /A ₂	45.64 ± 0.34bc	2.21 ± 0.01c
T ₂ /A ₃	46.86 ± 0.29b	2.46 ± 0.02c	T ₃ /A ₃	42.52 ± 0.41ef	1.86 ± 0.01fg
T ₂ /B ₁	38.38 ± 0.54f	1.59 ± 0.01g	T ₃ /B ₁	44.34 ± 0.60cd	2.07 ± 0.02d
T ₂ /B ₂	48.64 ± 0.33a	2.96 ± 0.04a	T ₃ /B ₂	46.55 ± 0.41ab	2.32 ± 0.09b
T ₂ /B ₃	43.67 ± 0.32d	2.02 ± 0.02e	T ₃ /B ₃	47.72 ± 0.30a	2.56 ± 0.01a
T ₂ /C ₁	40.86 ± 0.53e	1.71 ± 0.01f	T ₃ /C ₁	43.58 ± 0.62de	1.96 ± 0.02e
T ₂ /C ₂	48.62 ± 0.75a	2.82 ± 0.08b	T ₃ /C ₂	42.77 ± 0.31ef	1.92 ± 0.02ef
T ₂ /C ₃	45.51 ± 0.37c	2.17 ± 0.01d	T ₃ /C ₃	47.53 ± 0.77a	2.53 ± 0.01a
T ₄ /A ₁	24.42 ± 0.54d	0.96 ± 0.01g	T ₅ /A ₁	29.76 ± 0.47f	1.24 ± 0.01i
T ₄ /A ₂	29.07 ± 0.20b	1.21 ± 0.01c	T ₅ /A ₂	34.63 ± 0.74d	1.44 ± 0.01f
T ₄ /A ₃	33.91 ± 0.38a	1.40 ± 0.01a	T ₅ /A ₃	45.31 ± 0.33a	2.13 ± 0.01a
T ₄ /B ₁	17.70 ± 0.34f	0.62 ± 0.01i	T ₅ /B ₁	32.37 ± 0.38e	1.32 ± 0.01g
T ₄ /B ₂	26.70 ± 0.39c	1.16 ± 0.01d	T ₅ /B ₂	35.39 ± 0.58cd	1.48 ± 0.01e
T ₄ /B ₃	32.88 ± 0.77a	1.36 ± 0.01b	T ₅ /B ₃	41.39 ± 0.61b	1.77 ± 0.01b
T ₄ /C ₁	25.86 ± 0.28c	1.01 ± 0.01f	T ₅ /C ₁	40.39 ± 0.57b	1.66 ± 0.01c
T ₄ /C ₂	21.74 ± 0.32e	0.81 ± 0.02h	T ₅ /C ₂	30.65 ± 0.50f	1.27 ± 0.01h
T ₄ /C ₃	26.37 ± 0.27c	1.12 ± 0.01c	T ₅ /C ₃	36.77 ± 0.35c	1.52 ± 0.01d

Values are presented as mean ± SE ($n = 3$). Different lowercase letters within the same column indicate significant differences among the listed substrate–container treatment combinations according to Tukey’s multiple comparison test at $p < 0.05$. CK indicates the control substrate treatment; T₁–T₅ represent different substrate treatments, and A₁–C₃ represent different container treatments. DM indicates dry mass.

Based on the evident effects of container size and material, differences in dry matter accumulation among substrate treatments were further examined. Under the same container conditions, aboveground and belowground dry mass in all lightweight composite substrate treatments were significantly higher than those in CK, indicating that substrate formulation played an important regulatory role in biomass accumulation. Among the substrates, T₃ consistently resulted in the highest or second-highest aboveground and belowground dry mass under most container conditions, demonstrating a relatively stable biomass-promoting effect. T₂ and T₅ ranked next, whereas the promoting effects of T₁ and T₄ were comparatively weaker, although still significantly superior to CK. Differences among substrate treatments were more pronounced in medium and large containers, while such differences were relatively reduced in small containers.

Overall, container size was identified as the primary structural factor affecting dry matter accumulation in *Z. schneideriana* container seedlings, whereas substrate formulation exerted an additional enhancing effect on both aboveground and belowground dry mass. When sufficient growing space was provided, the biomass-promoting advantages of lightweight composite substrates were more fully expressed, resulting in a significant improvement in seedling dry matter production.

3.5. Effects of Different Container–Substrate Treatments on Nutrient Contents of *Zelkova schneideriana*

Significant differences in total nitrogen (N), total phosphorus (P), and total potassium (K) contents in *Zelkova schneideriana* seedlings were observed among treatments (Table 7). Overall, similar variation patterns were detected for N, P, and K contents across treatments. Seedlings grown in lightweight composite substrates generally exhibited higher nutrient contents than those grown in the control substrate (CK), and marked differences in nutrient accumulation were observed under different container conditions.

Table 7. Nutrient contents of *Zelkova schneideriana* Hand.-Mazz. seedlings under different substrate–container treatments.

Substrate– Container Combination	N (g·kg ^{−1})	P (g·kg ^{−1})	K (g·kg ^{−1})	Substrate– Container Combination	N (g·kg ^{−1})	P (g·kg ^{−1})	K (g·kg ^{−1})
CK/A ₁	26.05 ± 0.39a	6.22 ± 0.09f	28.16 ± 0.11c	T ₁ /A ₁	19.18 ± 0.26c	5.41 ± 0.06b	26.59 ± 0.08a
CK/A ₂	23.78 ± 0.13c	6.50 ± 0.04e	26.04 ± 0.34d	T ₁ /A ₂	20.33 ± 0.34b	6.00 ± 0.07a	23.71 ± 0.31c
CK/A ₃	25.53 ± 0.17a	7.25 ± 0.10c	29.69 ± 0.32b	T ₁ /A ₃	22.12 ± 0.25a	5.18 ± 0.08c	22.01 ± 0.38d
CK/B ₁	22.61 ± 0.31d	7.92 ± 0.05a	28.14 ± 0.21c	T ₁ /B ₁	20.34 ± 0.20b	5.27 ± 0.06bc	22.79 ± 0.01cd
CK/B ₂	24.69 ± 0.20b	7.06 ± 0.07cd	29.75 ± 0.29b	T ₁ /B ₂	18.18 ± 0.26de	4.72 ± 0.03e	25.09 ± 0.13b
CK/B ₃	22.79 ± 0.18d	7.55 ± 0.02b	31.16 ± 0.12a	T ₁ /B ₃	17.51 ± 0.30e	4.91 ± 0.04d	20.96 ± 0.27e
CK/C ₁	23.54 ± 0.19c	7.05 ± 0.01d	30.94 ± 0.27a	T ₁ /C ₁	18.37 ± 0.16d	5.44 ± 0.06b	23.71 ± 0.86c
CK/C ₂	21.86 ± 0.12e	6.53 ± 0.08e	28.02 ± 0.30c	T ₁ /C ₂	20.36 ± 0.34b	4.39 ± 0.06f	21.87 ± 0.32de
CK/C ₃	23.90 ± 0.12c	7.12 ± 0.06cd	31.01 ± 0.34a	T ₁ /C ₃	18.36 ± 0.26d	4.84 ± 0.03de	19.03 ± 0.32f
T ₂ /A ₁	18.67 ± 0.26e	6.62 ± 0.16a	27.78 ± 0.16c	T ₃ /A ₁	25.43 ± 0.18b	8.34 ± 0.11a	32.33 ± 0.23c
T ₂ /A ₂	19.50 ± 0.33d	6.29 ± 0.06b	23.68 ± 0.25e	T ₃ /A ₂	22.98 ± 0.19ef	7.09 ± 0.15d	35.16 ± 0.28a
T ₂ /A ₃	21.37 ± 0.16b	5.95 ± 0.10cd	26.78 ± 0.33d	T ₃ /A ₃	23.52 ± 0.17de	7.54 ± 0.07c	32.90 ± 0.11c
T ₂ /B ₁	18.75 ± 0.26e	6.31 ± 0.14b	23.15 ± 0.26e	T ₃ /B ₁	26.29 ± 0.17a	7.74 ± 0.17b	30.04 ± 0.30e
T ₂ /B ₂	22.38 ± 0.33a	5.12 ± 0.01f	29.20 ± 0.40b	T ₃ /B ₂	24.71 ± 0.28c	6.92 ± 0.04e	28.64 ± 0.16f
T ₂ /B ₃	21.10 ± 0.18b	5.50 ± 0.11e	22.42 ± 0.17f	T ₃ /B ₃	26.41 ± 0.15a	5.97 ± 0.07g	26.16 ± 0.28g
T ₂ /C ₁	17.34 ± 0.21f	6.10 ± 0.08c	28.94 ± 0.29b	T ₃ /C ₁	22.46 ± 0.22f	6.61 ± 0.10f	25.67 ± 0.13g
T ₂ /C ₂	18.56 ± 0.24e	5.88 ± 0.09d	26.29 ± 0.13d	T ₃ /C ₂	20.80 ± 0.12g	7.42 ± 0.06c	33.72 ± 0.01b
T ₂ /C ₃	20.28 ± 0.27c	5.03 ± 0.09f	30.13 ± 0.24a	T ₃ /C ₃	24.00 ± 0.33d	6.95 ± 0.04de	31.44 ± 0.23d
T ₄ /A ₁	24.20 ± 0.33a	5.23 ± 0.14e	26.83 ± 0.18a	T ₅ /A ₁	23.43 ± 0.17e	8.25 ± 0.02bc	35.98 ± 0.06b
T ₄ /A ₂	20.59 ± 0.26c	5.76 ± 0.08bc	20.98 ± 0.23f	T ₅ /A ₂	22.60 ± 0.24f	7.75 ± 0.06d	34.17 ± 0.17c
T ₄ /A ₃	19.39 ± 0.15d	5.01 ± 0.08fg	22.93 ± 0.09d	T ₅ /A ₃	25.30 ± 0.12c	8.56 ± 0.15a	32.23 ± 0.37d
T ₄ /B ₁	22.06 ± 0.24b	5.02 ± 0.11f	22.37 ± 0.12e	T ₅ /B ₁	27.47 ± 0.19a	8.34 ± 0.06b	37.33 ± 0.16ab
T ₄ /B ₂	20.08 ± 0.09c	5.88 ± 0.03b	25.67 ± 0.24b	T ₅ /B ₂	24.23 ± 0.17d	7.80 ± 0.07d	31.92 ± 0.63d
T ₄ /B ₃	19.38 ± 0.21d	4.87 ± 0.05g	23.93 ± 0.19c	T ₅ /B ₃	25.42 ± 0.12c	7.04 ± 0.12f	29.62 ± 1.33e
T ₄ /C ₁	20.17 ± 0.19c	5.48 ± 0.07d	23.99 ± 0.06c	T ₅ /C ₁	27.23 ± 0.05a	8.14 ± 0.14c	37.57 ± 0.27a
T ₄ /C ₂	19.23 ± 0.22d	5.95 ± 0.10a	25.68 ± 0.26b	T ₅ /C ₂	24.44 ± 0.16d	7.37 ± 0.07e	32.49 ± 0.09d
T ₄ /C ₃	20.54 ± 0.37c	5.66 ± 0.09c	19.07 ± 0.27g	T ₅ /C ₃	25.89 ± 0.14b	7.70 ± 0.08d	34.27 ± 0.20c

Values are presented as mean ± SE ($n = 3$). Different lowercase letters within the same column indicate significant differences among the listed substrate–container treatment combinations according to Tukey’s multiple comparison test at $p < 0.05$. CK indicates the control substrate treatment; T₁–T₅ represent different substrate treatments, and A₁–C₃ represent different container treatments. N, total nitrogen; P, total phosphorus; K, total potassium.

From the perspective of container effects, under identical substrate conditions, container size had a significant influence on plant N, P, and K contents. As container size increased from small (13 cm × 13 cm) to medium and large sizes (18 cm × 18 cm and 23 cm × 23 cm), N, P, and K contents in plant tissues showed an overall increasing trend. Higher nutrient contents were generally observed in A₂ and A₃, B₂ and B₃, as well as C₂ and C₃ treatments, whereas relatively lower values occurred in A₁, B₁, and C₁ treatments. These results indicate that container volume imposes a clear limitation on nutrient uptake and accumulation. Differences among container materials were also evident, with B-type containers under medium and large sizes exhibiting comparatively higher N, P, and K contents.

Based on the evident effects of container size and material, differences in nutrient contents among substrate treatments were further examined. Under the same container conditions, all lightweight composite substrates resulted in higher N, P, and K contents than CK, indicating that substrate formulation played an important regulatory role in nutrient

uptake. Among the substrates, T₃ consistently produced the highest or second-highest N, P, and K contents under most container conditions, showing a relatively stable promoting effect. T₅ and T₂ ranked next, whereas the effects of T₁ and T₄ were comparatively weaker, although still superior to CK. Differences among substrate treatments were more pronounced in medium and large containers, while such differences were relatively reduced in small containers.

Overall, container size was identified as the primary structural factor influencing nutrient accumulation in *Z. schneideriana* seedlings, whereas substrate formulation exerted an additional enhancing effect on nutrient uptake and accumulation. When sufficient growing space was provided, the nutrient supply advantages of lightweight composite substrates were more fully expressed, resulting in a significant increase in plant N, P, and K accumulation.

3.6. Effects of Different Container–Substrate Treatments on Chlorophyll Content and Photosynthetic Characteristics of *Zelkova schneideriana*

Significant differences in chlorophyll content and photosynthetic physiological parameters of *Zelkova schneideriana* were observed among treatments (Figure 2, Table 8). Overall, similar variation trends were observed among chlorophyll content, net photosynthetic rate (Pn), stomatal conductance (Gs), and transpiration rate (Tr). Seedlings grown in lightweight composite substrates generally exhibited higher values than those grown in the control substrate (CK), and such differences tended to be more evident under medium and large container conditions.

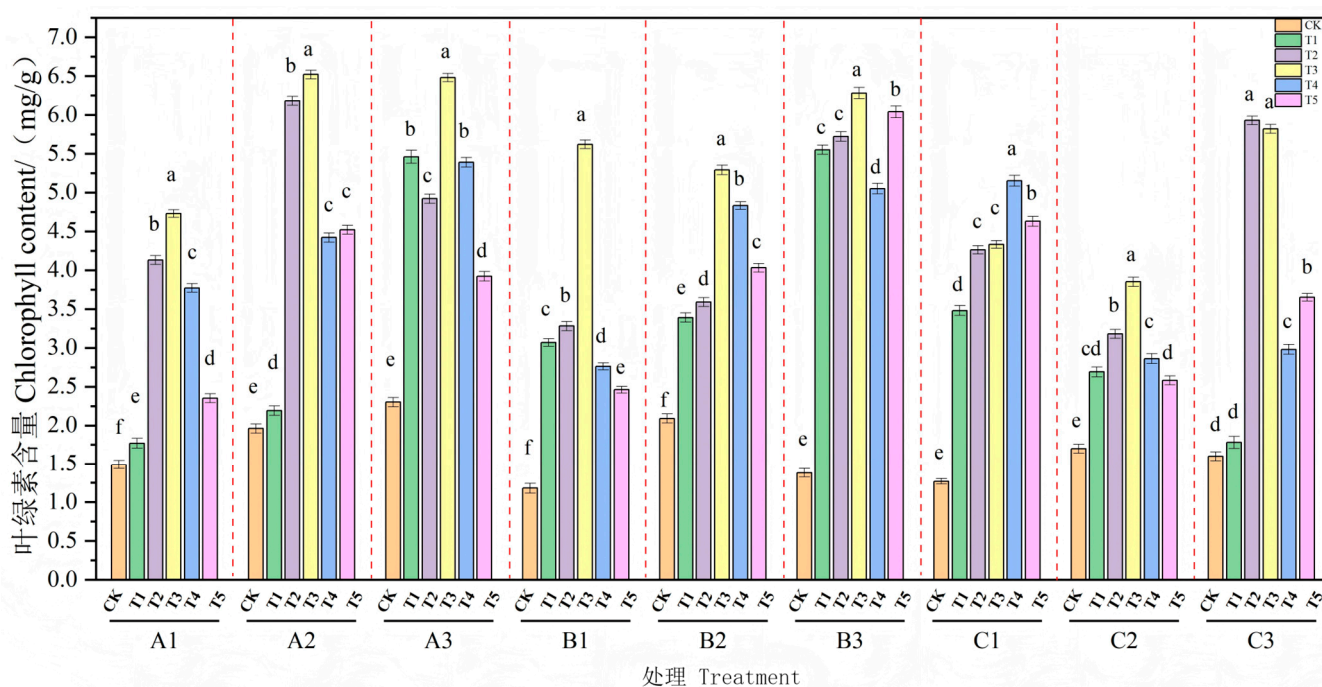


Figure 2. Chlorophyll content of *Zelkova schneideriana* Hand.-Mazz. under different substrate-container treatments. Values are presented as mean $\pm$ SE ($n = 3$). Within each container treatment (A₁–C₃), different lowercase letters indicate significant differences among substrate treatments (CK and T₁–T₅) according to Tukey's multiple comparison test at $p < 0.05$. CK indicates the control substrate treatment; T₁–T₅ represent different substrate treatments, and A₁–C₃ represent different container treatments.

Table 8. Photosynthetic parameters of *Zelkova schneideriana* Hand.-Mazz. seedlings under different substrate–container treatments.

Substrate–Container Combination	Pn ($\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$)	Ci ($\mu\text{mol}\cdot\text{mol}^{-1}$)	Gs ($\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$)	Tr ($\text{mmol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$)
CK/A ₁	10.66 ± 0.29c	304.36 ± 0.53b	0.19 ± 0.01bc	9.31 ± 0.20c
CK/A ₂	10.72 ± 0.34c	307.17 ± 0.96ab	0.20 ± 0.01b	9.77 ± 0.66c
CK/A ₃	14.23 ± 0.59a	316.39 ± 0.56a	0.31 ± 0.01a	13.36 ± 0.73a
CK/B ₁	12.44 ± 0.60b	305.60 ± 1.21b	0.22 ± 0.01b	10.73 ± 0.65b
CK/B ₂	8.71 ± 0.26d	234.61 ± 3.03d	0.09 ± 0.04d	4.78 ± 0.49f
CK/B ₃	14.73 ± 0.32a	235.78 ± 4.45d	0.15 ± 0.03c	7.78 ± 0.65d
CK/C ₁	10.60 ± 0.45c	257.10 ± 4.12c	0.10 ± 0.02d	6.76 ± 0.42e
CK/C ₂	7.49 ± 0.40e	250.94 ± 7.28c	0.08 ± 0.03d	4.91 ± 0.54f
CK/C ₃	8.73 ± 0.35d	205.93 ± 3.52e	0.07 ± 0.01d	4.56 ± 0.74f
T ₁ /A ₁	7.85 ± 0.56b	414.08 ± 6.79a	0.26 ± 0.03d	11.59 ± 0.52b
T ₁ /A ₂	5.29 ± 0.51e	333.89 ± 7.35d	0.12 ± 0.02f	6.13 ± 0.39d
T ₁ /A ₃	10.42 ± 0.94a	346.74 ± 3.78cd	0.37 ± 0.04bc	12.76 ± 0.53b
T ₁ /B ₁	5.57 ± 0.66de	373.94 ± 5.52b	0.41 ± 0.04ab	14.64 ± 0.72a
T ₁ /B ₂	10.64 ± 0.74a	354.15 ± 6.42c	0.45 ± 0.03a	14.70 ± 0.67a
T ₁ /B ₃	3.68 ± 1.11f	384.09 ± 6.20b	0.32 ± 0.04c	12.88 ± 0.36b
T ₁ /C ₁	7.58 ± 0.62bc	335.60 ± 4.30d	0.20 ± 0.03e	9.40 ± 0.47c
T ₁ /C ₂	6.50 ± 0.76cd	337.41 ± 5.75d	0.15 ± 0.01ef	7.59 ± 0.45d
T ₁ /C ₃	5.01 ± 0.76e	338.83 ± 5.96cd	0.13 ± 0.01f	7.37 ± 0.60d
T ₂ /A ₁	6.28 ± 0.65d	369.56 ± 5.32bc	0.30 ± 0.03ab	11.30 ± 0.64ab
T ₂ /A ₂	9.35 ± 0.54b	316.22 ± 7.19f	0.19 ± 0.02c	8.35 ± 0.62cd
T ₂ /A ₃	7.72 ± 0.40c	354.81 ± 3.94cd	0.27 ± 0.01b	10.67 ± 0.70ab
T ₂ /B ₁	5.08 ± 0.41de	404.37 ± 6.40a	0.33 ± 0.02a	11.74 ± 0.75a
T ₂ /B ₂	3.87 ± 0.30e	383.17 ± 3.07b	0.30 ± 0.02ab	10.79 ± 0.67ab
T ₂ /B ₃	9.49 ± 0.60ab	294.47 ± 3.78g	0.16 ± 0.02cd	7.50 ± 0.69de
T ₂ /C ₁	10.73 ± 0.34a	334.07 ± 7.99e	0.27 ± 0.01b	9.75 ± 0.41bc
T ₂ /C ₂	6.20 ± 0.62d	327.32 ± 5.89ef	0.13 ± 0.02d	6.54 ± 0.35e
T ₂ /C ₃	4.71 ± 0.46e	341.70 ± 6.22de	0.13 ± 0.02d	6.27 ± 0.57e
T ₃ /A ₁	4.76 ± 0.30b	425.13 ± 7.63a	0.29 ± 0.01ab	11.48 ± 0.59a
T ₃ /A ₂	7.65 ± 0.33a	339.45 ± 4.65d	0.20 ± 0.02de	9.38 ± 0.57bd
T ₃ /A ₃	3.44 ± 0.54b	382.10 ± 5.76c	0.22 ± 0.01cd	10.31 ± 0.58ab
T ₃ /B ₁	4.27 ± 0.51b	406.34 ± 3.85b	0.30 ± 0.02ab	11.60 ± 0.60a
T ₃ /B ₂	7.67 ± 0.41a	348.67 ± 5.64d	0.26 ± 0.01bc	11.48 ± 0.78a
T ₃ /B ₃	3.86 ± 0.39b	277.68 ± 4.27f	0.05 ± 0.01f	3.62 ± 0.34d
T ₃ /C ₁	8.38 ± 0.50a	315.00 ± 6.47e	0.17 ± 0.01e	8.31 ± 0.58c
T ₃ /C ₂	4.61 ± 0.31b	390.48 ± 4.61c	0.33 ± 0.02a	11.56 ± 0.63a
T ₃ /C ₃	8.41 ± 0.83a	349.21 ± 5.44d	0.30 ± 0.02ab	11.85 ± 0.56a
T ₄ /A ₁	15.72 ± 0.55b	318.04 ± 6.70b	0.38 ± 0.036a	14.67 ± 0.68a
T ₄ /A ₂	17.64 ± 0.70a	305.94 ± 12.43c	0.37 ± 0.02a	14.51 ± 0.60a
T ₄ /A ₃	15.80 ± 0.87b	268.70 ± 6.93d	0.23 ± 0.03bc	11.42 ± 0.58b
T ₄ /B ₁	10.20 ± 0.67d	266.44 ± 7.57d	0.12 ± 0.03d	6.80 ± 0.36d
T ₄ /B ₂	11.95 ± 0.89c	265.94 ± 7.06d	0.14 ± 0.03d	7.69 ± 0.48d
T ₄ /B ₃	8.63 ± 0.57e	337.62 ± 6.61a	0.22 ± 0.04bc	10.45 ± 0.58bc
T ₄ /C ₁	11.18 ± 0.43cd	346.69 ± 6.63a	0.34 ± 0.04a	13.46 ± 0.51a
T ₄ /C ₂	11.74 ± 0.84c	308.13 ± 8.67bc	0.21 ± 0.05c	9.50 ± 0.60c
T ₄ /C ₃	14.75 ± 0.44b	312.00 ± 2.53bc	0.28 ± 0.03b	11.40 ± 0.60b
T ₅ /A ₁	4.42 ± 0.90g	332.72 ± 6.04bc	0.10 ± 0.02e	5.29 ± 1.20f
T ₅ /A ₂	7.46 ± 0.85f	324.80 ± 7.38bcd	0.18 ± 0.02cd	8.38 ± 1.10de
T ₅ /A ₃	7.48 ± 1.24ef	351.72 ± 8.70a	0.27 ± 0.02ab	12.45 ± 1.44a
T ₅ /B ₁	10.71 ± 0.57c	336.16 ± 7.07b	0.28 ± 0.03a	11.57 ± 1.27ab
T ₅ /B ₂	8.70 ± 0.48de	304.61 ± 11.00e	0.15 ± 0.03cde	7.37 ± 1.13e
T ₅ /B ₃	6.76 ± 0.58f	318.48 ± 6.78d	0.13 ± 0.02de	6.69 ± 1.31ef
T ₅ /C ₁	13.81 ± 0.90b	288.66 ± 6.49f	0.20 ± 0.08bcd	10.37 ± 1.06bc
T ₅ /C ₂	12.03 ± 0.71b	277.54 ± 5.49f	0.17 ± 0.04cde	8.39 ± 1.00de
T ₅ /C ₃	9.71 ± 0.55cd	322.03 ± 10.37cd	0.21 ± 0.04abc	9.56 ± 1.06cd

Values are presented as mean ± SE ($n = 3$). Different lowercase letters within the same column indicate significant differences among the listed substrate–container treatment combinations according to Tukey's multiple comparison test at $p < 0.05$. CK indicates the control substrate treatment; T₁–T₅ represent different substrate treatments, and A₁–C₃ represent different container treatments. Pn, net photosynthetic rate; Ci, intercellular CO₂ concentration; Gs, stomatal conductance; Tr, transpiration rate.

From the perspective of treatment combinations, chlorophyll content and photosynthetic parameters generally tended to be higher under medium and large container conditions than under small container conditions. Higher chlorophyll content and photosynthetic parameter values were often observed in A₂ and A₃, B₂ and B₃, as well as C₂ and C₃ treatments, whereas relatively lower values occurred in A₁, B₁, and C₁ treatments. Differences among container materials were also observable, with B-type containers under medium and large sizes generally showing comparatively better photosynthetic performance.

Under the same container conditions, most lightweight composite substrates resulted in higher chlorophyll content and relatively higher Pn, Gs, and Tr values than CK, indicating that substrate formulation played an important regulatory role in leaf photosynthetic performance. Among the substrates, T₃ generally produced the highest or second-highest chlorophyll content under most container conditions and showed relatively stable advantages in Pn, Gs, and Tr. T₄ and T₂ ranked next, whereas the promoting effects of T₁ and T₅ were comparatively weaker. Differences among substrate treatments were more pronounced in medium and large containers, while such differences were relatively reduced in small containers.

Overall, both container conditions and substrate formulation contributed to variation in chlorophyll content and photosynthetic physiological traits of *Z. schneideriana* seedlings. Under conditions with sufficient growing space, the promoting effects of lightweight composite substrates on leaf photosynthetic performance were more fully expressed.

As shown in Table 3, substrate composition, container type, and container size all significantly affected chlorophyll content, indicating that chlorophyll accumulation was jointly regulated by these three factors.

3.7. Effects of Different Container–Substrate Nursery Treatments on Root Morphological Traits of *Zelkova schneideriana*

Significant differences in root morphological traits of container-grown *Zelkova schneideriana* seedlings were observed among treatments (Table 9). Overall, clear differentiation was found among treatments in terms of total root length, root surface area, root volume, root tip number, and average root diameter, with generally consistent variation patterns across these indicators.

From the perspective of container effects, under identical substrate conditions, container size showed a clear influence on root morphological traits. As container size increased from small (13 cm × 13 cm) to medium and large sizes (18 cm × 18 cm and 23 cm × 23 cm), total root length, root surface area, root volume, and root tip number generally showed increasing trends. Higher root biomass and root quantity were generally observed in A₂ and A₃, B₂ and B₃, as well as C₂ and C₃ treatments, whereas root development was relatively restricted in A₁, B₁, and C₁ treatments. These results indicate that container volume imposes a clear limitation on root system expansion. Differences among container materials were also evident, with B-type containers under medium and large sizes exhibiting overall superior root morphological performance.

Based on the evident effects of container size and material, differences in root morphological traits among substrate treatments were further examined. Under the same container conditions, all lightweight composite substrates resulted in higher total root length, root surface area, root volume, and root tip number than the control substrate (CK), indicating that substrate formulation played an important regulatory role in root growth. Among the substrates, T₂ and T₃ consistently produced the highest or second-highest values for most root morphological traits under the majority of container conditions, showing relatively stable promoting effects. The promoting effects of T₁, T₄, and T₅ were comparatively weaker, although still superior to CK. Differences among substrate treatments were more

pronounced in medium and large containers, while such differences were relatively reduced in small containers.

Table 9. Root morphological traits of *Zelkova schneideriana* Hand.-Mazz. seedlings under different substrate–container treatments.

Substrate–Container Combination	Total Root Length (cm)	Root Surface Area (cm ²)	Root Volume (mm ³)	Number of Root Tips	Mean Root Diameter (mm)
CK/A ₁	259.48 ± 2.51f	111.27 ± 1.15f	10.86 ± 0.98d	3771.00 ± 7.00h	0.54 ± 0.01e
CK/A ₂	409.99 ± 4.49c	220.57 ± 2.58c	13.07 ± 1.49bcd	6514.67 ± 3.71d	0.66 ± 0.02d
CK/A ₃	447.13 ± 4.27b	347.35 ± 3.49b	16.45 ± 1.20a	6778.67 ± 5.20b	0.76 ± 0.02c
CK/B ₁	355.33 ± 2.71d	205.81 ± 3.55d	15.42 ± 0.78ab	6323.33 ± 7.88e	0.93 ± 0.03b
CK/B ₂	487.78 ± 2.75a	374.66 ± 1.80a	15.64 ± 0.72ab	6883.00 ± 4.16a	1.24 ± 0.02a
CK/B ₃	453.20 ± 3.20b	214.60 ± 2.15cd	12.47 ± 0.63cd	6628.67 ± 4.66c	0.43 ± 0.03f
CK/C ₁	363.11 ± 2.65d	207.89 ± 5.82d	14.72 ± 0.29abc	6288.67 ± 26.77e	0.90 ± 0.04b
CK/C ₂	306.62 ± 5.83e	118.96 ± 4.81f	11.46 ± 0.72d	4805.33 ± 48.51g	0.49 ± 0.03ef
CK/C ₃	314.25 ± 6.75e	129.44 ± 4.96e	12.64 ± 0.61cd	5231.33 ± 26.20f	0.65 ± 0.03d
T ₁ /A ₁	419.79 ± 5.04b	292.23 ± 4.62a	15.94 ± 0.53a	6749.67 ± 42.25a	0.77 ± 0.03c
T ₁ /A ₂	388.38 ± 5.64c	133.42 ± 2.13d	11.41 ± 0.35c	5651.33 ± 37.23c	0.48 ± 0.03ef
T ₁ /A ₃	371.76 ± 3.05d	140.27 ± 3.53d	11.85 ± 0.49c	5655.67 ± 40.07c	0.52 ± 0.02ef
T ₁ /B ₁	282.41 ± 4.58g	121.03 ± 6.32e	11.46 ± 0.71c	4878.33 ± 34.37d	0.58 ± 0.03de
T ₁ /B ₂	453.75 ± 7.93a	287.38 ± 4.29a	14.44 ± 0.43b	6724.67 ± 68.86	0.57 ± 0.02de
T ₁ /B ₃	378.28 ± 4.83cd	253.96 ± 2.92b	15.83 ± 0.58a	6514.33 ± 55.48b	0.92 ± 0.05b
T ₁ /C ₁	338.12 ± 5.02e	228.52 ± 5.30c	6.25 ± 0.52d	6456.00 ± 35.21b	1.04 ± 0.04a
T ₁ /C ₂	309.69 ± 5.20f	118.23 ± 4.97e	1.10 ± 0.14e	4922.00 ± 28.11d	0.44 ± 0.03f
T ₁ /C ₃	320.36 ± 6.00f	114.76 ± 2.96e	1.60 ± 0.29e	4657.67 ± 41.38e	0.67 ± 0.03cd
T ₂ /A ₁	410.90 ± 5.59bc	292.79 ± 4.47c	15.98 ± 0.52c	6839.00 ± 76.42a	0.81 ± 0.03c
T ₂ /A ₂	339.96 ± 5.40d	117.88 ± 3.13g	10.87 ± 0.63d	4330.33 ± 41.92f	0.43 ± 0.03f
T ₂ /A ₃	404.63 ± 6.74c	218.39 ± 5.06d	13.61 ± 0.42	6243.33 ± 34.18c	0.68 ± 0.02d
T ₂ /B ₁	407.09 ± 3.39c	353.18 ± 3.06b	20.62 ± 0.73b	6634.67 ± 62.52b	1.18 ± 0.06b
T ₂ /B ₂	420.51 ± 4.18b	196.04 ± 2.79e	12.61 ± 0.39d	5929.67 ± 57.44d	0.53 ± 0.03ef
T ₂ /B ₃	477.10 ± 3.91a	381.64 ± 5.54a	23.7 ± 0.73a	6866.67 ± 77.98a	1.73 ± 0.03a
T ₂ /C ₁	288.08 ± 4.15f	128.95 ± 5.76g	11.42 ± 0.61	4357.33 ± 67.22f	0.66 ± 0.03d
T ₂ /C ₂	317.85 ± 4.99e	173.35 ± 5.96f	13.77 ± 0.57d	5468.33 ± 57.02e	0.85 ± 0.02c
T ₂ /C ₃	413.32 ± 2.57bc	186.64 ± 3.51e	12.54 ± 0.42d	5564.00 ± 61.02e	0.54 ± 0.03e
T ₃ /A ₁	395.06 ± 2.86d	221.69 ± 6.00d	14.61 ± 0.61b	6479.67 ± 34.85b	0.78 ± 0.02a
T ₃ /A ₂	333.81 ± 2.81e	128.44 ± 4.95f	11.55 ± 0.58c	4839.33 ± 61.31c	0.51 ± 0.02d
T ₃ /A ₃	439.17 ± 5.59c	368.58 ± 5.76a	19.71 ± 0.56a	6826.00 ± 60.92a	0.66 ± 0.03b
T ₃ /B ₁	268.84 ± 3.80g	118.11 ± 4.90f	11.51 ± 0.69c	4558.33 ± 82.17d	0.64 ± 0.02bc
T ₃ /B ₂	472.87 ± 2.57a	306.82 ± 3.00b	14.41 ± 0.59b	6783.33 ± 58.35a	0.61 ± 0.03bc
T ₃ /B ₃	455.62 ± 2.41b	287.61 ± 3.80c	14.45 ± 0.41b	6765.33 ± 37.5a	0.57 ± 0.02cd
T ₃ /C ₁	256.16 ± 3.65h	118.81 ± 5.04f	11.41 ± 0.61c	3946.33 ± 37.29d	0.69 ± 0.03b
T ₃ /C ₂	397.37 ± 3.36d	204.58 ± 6.89e	14.71 ± 0.67b	6455.33 ± 35.02b	0.68 ± 0.03b
T ₃ /C ₃	323.46 ± 3.49f	122.82 ± 3.20f	11.75 ± 0.78c	4918.67 ± 60.09c	0.52 ± 0.02d
T ₄ /A ₁	431.13 ± 6.18a	246.85 ± 4.05a	13.56 ± 0.44b	6660.67 ± 85.39a	0.58 ± 0.03a
T ₄ /A ₂	227.17 ± 5.55e	109.00 ± 4.83d	10.79 ± 0.61c	3633.00 ± 43.96ef	0.46 ± 0.02c
T ₄ /A ₃	372.34 ± 3.87b	207.31 ± 3.46ce	13.04 ± 0.65c	5779.34 ± 38.87b	0.70 ± 0.02cd
T ₄ /B ₁	265.86 ± 3.22c	112.91 ± 8.28de	26.48 ± 0.58a	3748.00 ± 40.42e	0.41 ± 0.03cd
T ₄ /B ₂	238.88 ± 5.51de	110.06 ± 5.55de	10.34 ± 0.65c	3958.00 ± 39.73d	0.48 ± 0.03bc
T ₄ /B ₃	249.29 ± 5.38d	108.58 ± 5.34de	10.25 ± 0.63c	3637.00 ± 85.44ef	0.36 ± 0.01d
T ₄ /C ₁	271.72 ± 6.53c	120.92 ± 5.80cd	11.62 ± 0.66c	4788.67 ± 56.25c	0.62 ± 0.03a
T ₄ /C ₂	407.56 ± 5.98b	208.44 ± 4.95b	13.41 ± 0.27b	6541.67 ± 66.69a	0.63 ± 0.03a
T ₄ /C ₃	185.86 ± 3.07f	106.72 ± 3.90e	10.29 ± 0.53c	3577.33 ± 60.31f	0.56 ± 0.03ab
T ₅ /A ₁	161.37 ± 4.00h	104.33 ± 2.99f	10.22 ± 0.63d	3451.00 ± 77.57f	0.59 ± 0.02de
T ₅ /A ₂	295.49 ± 3.69g	129.11 ± 4.88e	11.61 ± 0.73cd	4466.67 ± 64.73e	0.69 ± 0.04cde
T ₅ /A ₃	377.57 ± 5.09cd	176.52 ± 3.28d	12.37 ± 0.66bc	5350.67 ± 66.21d	0.64 ± 0.02d
T ₅ /B ₁	346.88 ± 7.65e	260.56 ± 5.72a	17.45 ± 0.30a	6346.33 ± 66.56b	1.18 ± 0.04a
T ₅ /B ₂	405.75 ± 3.00b	211.77 ± 4.32c	13.45 ± 0.44b	6580.33 ± 55.44ac	0.66 ± 0.03cde
T ₅ /B ₃	389.17 ± 5.79c	167.31 ± 3.72d	12.57 ± 0.54bc	6153.33 ± 51.20	0.58 ± 0.03de
T ₅ /C ₁	366.89 ± 3.46d	177.27 ± 3.53d	13.34 ± 0.49b	6569.33 ± 41.28a	0.75 ± 0.04c
T ₅ /C ₂	425.25 ± 8.35a	213.82 ± 3.45bc	12.56 ± 0.48bc	6572.67 ± 75.78a	0.56 ± 0.04e
T ₅ /C ₃	327.89 ± 4.09f	223.66 ± 3.11b	16.17 ± 0.60a	6473.33 ± 83.31ab	1.03 ± 0.05b

Values are presented as mean ± SE ($n = 3$). Different lowercase letters within the same column indicate significant differences among the listed substrate–container treatment combinations according to Tukey’s multiple comparison test at $p < 0.05$. CK indicates the control substrate treatment; T₁–T₅ represent different substrate treatments, and A₁–C₃ represent different container treatments.

In terms of root architectural characteristics, seedlings grown in T₂ and T₃ substrates exhibited increased root quantity and root system volume while maintaining moderate average root diameter, forming a “fine and dense” root system architecture that is conducive

to expanding the absorptive surface area. In contrast, seedlings grown in CK exhibited relatively lower root quantity and root biomass.

Overall, container size was identified as the primary structural factor influencing root morphological development of *Z. schneideriana* container seedlings, whereas substrate formulation exerted an additional enhancing effect on root growth. When sufficient growing space was provided, the promoting effects of lightweight composite substrates on root expansion and branching were more fully expressed.

3.8. Principal Component Analysis of 17 Traits of *Zelkova schneideriana* Under Different Container–Substrate Nursery Treatments

To comprehensively evaluate the growth quality and physiological–ecological characteristics of container-grown *Zelkova schneideriana* seedlings under different container and substrate conditions, principal component analysis (PCA) was performed based on 17 traits, including seedling height, ground diameter, aboveground and belowground dry mass, chlorophyll content, photosynthetic parameters, plant nutrient contents, and root morphological traits. The results showed that the first five principal components had eigenvalues greater than 1, with a cumulative variance contribution rate of 82.577%, indicating that these components adequately represented the information contained in the original variables (Table 10).

Table 10. Eigenvectors of 17 evaluated traits in each principal component for *Zelkova schneideriana* Hand.-Mazz. seedlings under different substrate–container treatments.

Indicator	Factor1	Factor2	Factor3	Factor4	Factor5
Total nitrogen (TN)	0.07	0.20	−0.41	0.22	0.64
Total phosphorus (TP)	0.67	−0.04	−0.25	−0.39	0.55
Total potassium (TK)	−0.60	0.18	0.03	0.51	−0.4
Seedling height	0.92	−0.10	−0.13	0.25	−0.13
Ground diameter	0.87	−0.17	−0.04	0.22	−0.11
Aboveground dry mass	0.91	−0.09	−0.18	0.25	−0.12
Belowground dry mass	0.89	−0.09	−0.22	0.21	−0.12
Total chlorophyll content	0.84	−0.17	−0.07	0.22	−0.05
Net photosynthetic rate (Pn)	−0.42	0.00	0.31	0.67	0.39
Intercellular CO ₂ concentration (Ci)	0.62	0.02	0.50	−0.43	−0.20
Stomatal conductance (Gs)	0.38	0.08	0.89	0.04	0.13
Transpiration rate (Tr)	0.31	0.08	0.90	0.11	0.22
Total root length	0.19	0.83	−0.08	−0.02	0.04
Root surface area	0.20	0.93	0.00	−0.07	−0.04
Root volume	0.19	0.64	−0.06	0.12	0.06
Number of root tips	0.13	0.90	0.00	−0.05	0.03
Mean root diameter	0.02	0.69	−0.07	−0.02	−0.28
Eigenvalue	5.65	3.42	2.30	1.41	1.26
Variance (%)	33.22	20.11	13.54	8.30	7.41
Cumulative (%)	33.22	53.33	66.87	75.17	82.58

TN, total nitrogen; TP, total phosphorus; TK, total potassium; Pn, net photosynthetic rate; Ci, intercellular CO₂ concentration; Gs, stomatal conductance; Tr, transpiration rate. Aboveground dry mass and belowground dry mass were used instead of dry weight. Eigenvalue indicates the variance explained by each principal component.

The first principal component (Factor 1) explained 33.215% of the total variance and exhibited high positive loadings for seedling height, ground diameter, aboveground and belowground dry mass, total chlorophyll content, and plant total nitrogen and total phosphorus contents. This component reflects the integrated characteristics of vegetative growth, biomass accumulation, and nutrient uptake and was therefore defined as the “comprehensive growth and nutrient uptake factor.” This result indicates that overall seedling quality of *Z. schneideriana* is primarily regulated by vegetative growth performance and nutrient supply status.

The second principal component (Factor 2) accounted for 20.111% of the total variance and showed high loadings for total root length, root surface area, root volume, root tip number, and average root diameter. This component mainly reflects root quantity and spatial expansion characteristics and was defined as the “root morphological structure factor.” These results suggest that root system development is an important component influencing the comprehensive quality of container-grown seedlings.

The third principal component (Factor 3), explaining 13.544% of the total variance, exhibited high positive loadings for stomatal conductance, transpiration rate, and intercellular CO₂ concentration, reflecting leaf gas exchange and stomatal regulation characteristics. This component was defined as the “stomatal regulation and gas exchange factor.”

The fourth principal component (Factor 4) explained 8.298% of the total variance and was mainly associated with net photosynthetic rate, reflecting differences in instantaneous photosynthetic efficiency. This component was defined as the “photosynthetic efficiency factor.”

The fifth principal component (Factor 5) accounted for 7.409% of the total variance and was mainly related to plant total nitrogen and total phosphorus contents, reflecting supplementary characteristics of mineral nutrient status. This component was defined as the “mineral nutrient supplementation factor.”

Overall, the first two principal components together explained 53.326% of the total variance, indicating that vegetative growth and root morphological traits are the core factors determining the comprehensive quality of container-grown *Z. schneideriana* seedlings, while photosynthetic physiological traits and nutrient status act as important supplementary factors. The PCA results further corroborate the conclusions of the single-factor analyses, demonstrating that container size and substrate conditions have significant effects on seedling growth, nutrient uptake, and root system development.

3.9. Comprehensive Evaluation of 17 Traits of *Zelkova schneideriana* Under Different Container–Substrate Nursery Treatments

Based on the results of the single-factor analyses and principal component analysis, a comprehensive evaluation was conducted to quantitatively assess the overall growth quality of container-grown *Zelkova schneideriana* seedlings under different container and substrate conditions. According to the PCA results, a comprehensive evaluation function was constructed, and 17 traits—including seedling height, ground diameter, dry matter accumulation, chlorophyll content, photosynthetic characteristics, plant nutrient contents, and root morphological traits—were integrated to calculate comprehensive scores and rank different treatments (Table 11).

The comprehensive score (F) results revealed marked differences in overall seedling quality among treatments. From the perspective of container effects, under identical substrate conditions, container size showed a clear influence on comprehensive scores. Treatments with medium and large container sizes (A₃, B₂, B₃, C₂, and C₃) generally exhibited higher comprehensive scores than those with small container sizes (A₁, B₁, and C₁), and many of these treatments ranked among the top positions. These results indicate that container size was an important structural factor affecting the comprehensive quality of *Z. schneideriana* container seedlings. However, the comprehensive ranking was jointly determined by multiple traits, container type, and substrate formulation, rather than by pot size alone. Differences among container materials were also observed, with B-type containers under medium and large sizes showing relatively higher comprehensive scores.

Table 11. Comprehensive scores and rankings of different substrate–container combinations based on principal component analysis for *Zelkova schneideriana* Hand.-Mazz. seedlings.

Substrate–Container Combination	PC1	PC2	PC3	PC4	PC5	Comprehensive Score (F)	Rank
CK/A ₁	0.11	0.19	0.57	0.43	0.91	0.33	48
CK/A ₂	0.27	0.58	0.58	0.43	0.78	0.45	36
CK/A ₃	0.43	0.79	0.74	0.71	0.92	0.62	8
CK/B ₁	0.11	0.63	0.68	0.34	0.80	0.42	40
CK/B ₂	0.15	0.94	0.27	0.41	0.60	0.43	39
CK/B ₃	0.06	0.58	0.50	0.57	0.93	0.36	45
CK/C ₁	0.03	0.61	0.41	0.39	0.72	0.34	47
CK/C ₂	0.08	0.25	0.34	0.33	0.58	0.24	53
CK/C ₃	0.00	0.35	0.27	0.44	0.73	0.25	52
T ₁ /A ₁	0.32	0.71	0.82	0.13	0.41	0.48	29
T ₁ /A ₂	0.25	0.35	0.46	0.14	0.43	0.31	49
T ₁ /A ₃	0.61	0.32	0.80	0.61	0.65	0.55	22
T ₁ /B ₁	0.47	0.23	0.95	0.28	0.52	0.48	32
T ₁ /B ₂	0.51	0.64	1.00	0.46	0.54	0.59	15
T ₁ /B ₃	0.64	0.58	0.81	0.25	0.16	0.56	21
T ₁ /C ₁	0.38	0.46	0.64	0.25	0.23	0.41	43
T ₁ /C ₂	0.34	0.08	0.54	0.21	0.38	0.29	51
T ₁ /C ₃	0.22	0.14	0.55	0.00	0.28	0.24	54
T ₂ /A ₁	0.66	0.64	0.71	0.45	0.20	0.59	14
T ₂ /A ₂	0.64	0.11	0.51	0.67	0.34	0.45	37
T ₂ /A ₃	0.77	0.47	0.59	0.66	0.30	0.60	12
T ₂ /B ₁	0.69	0.82	0.75	0.33	0.12	0.65	5
T ₂ /B ₂	0.80	0.42	0.56	0.55	0.24	0.59	13
T ₂ /B ₃	0.75	1.00	0.35	0.77	0.12	0.68	3
T ₂ /C ₁	0.57	0.16	0.67	0.66	0.20	0.46	34
T ₂ /C ₂	0.65	0.34	0.37	0.57	0.00	0.47	33
T ₂ /C ₃	0.73	0.34	0.35	0.60	0.06	0.48	30
T ₃ /A ₁	0.90	0.51	0.58	0.12	0.93	0.67	4
T ₃ /A ₂	0.94	0.13	0.41	0.40	0.91	0.58	17
T ₃ /A ₃	1.00	0.68	0.45	0.20	0.82	0.71	1
T ₃ /B ₁	0.93	0.14	0.57	0.23	0.93	0.61	11
T ₃ /B ₂	0.93	0.60	0.50	0.38	0.99	0.70	2
T ₃ /B ₃	0.91	0.52	0.00	0.41	0.80	0.58	18
T ₃ /C ₁	0.72	0.08	0.39	0.38	0.79	0.48	28
T ₃ /C ₂	0.87	0.46	0.64	0.08	0.80	0.63	6
T ₃ /C ₃	0.94	0.16	0.56	0.44	1.00	0.63	7
T ₄ /A ₁	0.49	0.60	0.86	0.79	0.94	0.62	10
T ₄ /A ₂	0.48	0.04	0.90	0.85	0.83	0.50	25
T ₄ /A ₃	0.52	0.31	0.65	0.86	0.65	0.450	26
T ₄ /B ₁	0.29	0.26	0.41	0.63	0.69	0.39	44
T ₄ /B ₂	0.39	0.04	0.47	0.70	0.49	0.35	46
T ₄ /B ₃	0.54	0.00	0.65	0.55	0.38	0.41	42
T ₄ /C ₁	0.53	0.19	0.85	0.60	0.55	0.50	24
T ₄ /C ₂	0.38	0.51	0.63	0.52	0.51	0.46	35
T ₄ /C ₃	0.39	0.02	0.75	0.64	0.70	0.42	41
T ₅ /A ₁	0.35	0.02	0.34	0.43	0.28	0.31	50
T ₅ /A ₂	0.51	0.22	0.48	0.63	0.35	0.44	38
T ₅ /A ₃	0.69	0.39	0.60	0.70	0.55	0.59	16
T ₅ /B ₁	0.48	0.72	0.61	0.74	0.67	0.62	9
T ₅ /B ₂	0.52	0.52	0.39	0.66	0.51	0.50	27
T ₅ /B ₃	0.66	0.38	0.31	0.70	0.45	0.51	23
T ₅ /C ₁	0.54	0.49	0.47	1.00	0.75	0.57	19
T ₅ /C ₂	0.39	0.53	0.45	0.72	0.71	0.48	31
T ₅ /C ₃	0.54	0.59	0.49	0.74	0.54	0.57	20

PC1–PC5 represent the scores of the first five principal components. F indicates the comprehensive evaluation score calculated from the weighted principal component scores. CK indicates the control substrate treatment; T₁–T₅ represent different substrate treatments, and A₁–C₃ represent different container treatments. Treatments were ranked in descending order of the comprehensive score.

Based on the evident effects of container size, comprehensive evaluation results under different substrate conditions were further compared. Under the same container conditions, all lightweight composite substrates generally achieved higher comprehensive scores than the control substrate (CK), indicating that substrate formulation plays an important regulatory role in overall seedling quality. Among the substrates, T₃ consistently obtained higher comprehensive scores under most container conditions, demonstrating good stability and consistency. T₂, T₄, and T₅ ranked next, whereas T₁ and CK showed relatively lower comprehensive scores. Differences in ranking among substrate treatments were more pronounced under medium and large container conditions.

Overall, the comprehensive ranking results showed that top-performing treatments were mainly concentrated in combinations of medium and large containers with lightweight composite substrates, further validating the conclusions derived from the single-factor and principal component analyses. In general, container size plays a dominant role in the formation of comprehensive seedling quality of *Z. schneideriana*, while substrate formulation exerts an amplifying and optimizing effect on seedling growth performance. The comprehensive evaluation provides a quantitative basis for the selection of nursery techniques and their application in seedling production.

4. Discussion

4.1. Dominant Effects of Container Conditions on the Growth of *Zelkova schneideriana* Container Seedlings

The results of this study indicate that container conditions influenced vegetative growth, biomass accumulation, nutrient uptake, photosynthetic capacity, and root morphological traits of container-grown *Zelkova schneideriana* seedlings [35]. Based mainly on the trends observed for seedling height, ground diameter, chlorophyll content, photosynthetic parameters, and root morphological traits, container size appeared to be an important structural factor affecting seedling performance. In the comprehensive evaluation, medium and large container treatments also tended to achieve higher rankings overall, although some small-container treatments still performed better than certain medium-container treatments [36]. In the comprehensive evaluation, medium and large container treatments also tended to achieve higher rankings overall, although some small-container treatments still performed better than certain medium-container treatments. Recent studies on container-grown woody species have widely reported that limited container volume can lead to root confinement, altered root architecture, and reduced nutrient uptake efficiency, thereby constraining aboveground growth [37]. In contrast, increasing container volume can effectively alleviate spatial limitations on root growth, promote root expansion and biomass accumulation, and ultimately enhance overall seedling performance [38]. This pattern has been confirmed across a wide range of broadleaf and coniferous tree species [39].

Moreover, under the same container size, container material also influenced seedling growth [40]. Some container types exhibited relatively more stable performance in terms of root morphology, photosynthetic capacity, and nutrient accumulation, suggesting that container structural characteristics—such as aeration, drainage, and sidewall properties—may regulate seedling growth by modifying the rhizosphere microenvironment [41]. Recent and previous studies have further indicated that optimizing container structural design can improve root distribution patterns and enhance growth uniformity of container seedlings [5,42]. In the present study, some container types exhibited favorable performance under specific substrate and size combinations. In particular, B-type containers generally showed relatively better growth and comprehensive performance under medium- and large-size conditions, whereas nonwoven fabric containers may still provide potential advantages in rhizosphere aeration and drainage under certain nursery conditions. Therefore, the effects of container type should

be interpreted in relation to both structural properties and their interactions with substrate formulation and container size.

4.2. Regulatory Effects of Substrate Formulation on Seedling Growth and Physiological Traits

With the dominant effect of container size clearly established, substrate formulation played an additional regulatory role in the growth performance of *Z. schneideriana* container seedlings. Compared with the control substrate, all lightweight composite substrates generally exhibited superior performance in biomass accumulation, plant nutrient status, photosynthetic capacity, and root morphological development, indicating that optimization of substrate physicochemical properties can significantly improve the seedling growth environment [43].

Recent studies on substrates for container nursery production have suggested that reducing substrate bulk density, increasing total porosity, and optimizing the air–water balance are key approaches for improving seedling quality [44]. Lightweight composite substrates can enhance rhizosphere aeration and water-holding capacity, thereby facilitating root growth and nutrient uptake and promoting aboveground development [45]. The present results showed that the growth-promoting effects of substrate formulation were more pronounced under medium and large container conditions, indicating that the effective expression of substrate effects depends on the availability of sufficient root growth space.

4.3. Integrated Analysis of Substrate Component Proportions and Seedling Growth Responses

In this study, seven materials—yellow soil, peat soil, turf peat, perlite, vermiculite, rice husk, and sawdust—were combined at different volumetric ratios to formulate composite substrates. By integrating substrate physicochemical properties, seedling growth traits, physiological parameters, and principal component analysis results, clear directional relationships between substrate component proportions and seedling growth performance were identified.

An increased proportion of peat-based materials was associated with higher organic matter and total nitrogen contents, increased total porosity, and reduced bulk density, which collectively improved rhizosphere water retention and nutrient supply [46,47]. These changes promoted chlorophyll accumulation, enhanced photosynthetic capacity, and increased plant nutrient uptake [48]. Recent studies have consistently indicated that moderate incorporation of peat-based materials is an effective strategy for improving the overall performance of substrates used in container nursery systems. In the present study, treatments with higher proportions of peat-based materials showed superior performance across multiple growth and physiological indicators, consistent with these findings.

The appropriate incorporation of inorganic porous materials such as perlite and vermiculite markedly improved substrate aeration and non-capillary porosity, facilitating root elongation, branching, and spatial expansion [49]. Consequently, seedlings developed a “fine and dense” root system architecture, which is favorable for expanding the absorptive surface area for water and nutrient uptake [50]. In contrast, although rice husk and sawdust contributed to improving substrate structure, excessive proportions may have constrained seedling growth due to limited nutrient availability or temporary nutrient immobilization [51]. Treatments containing higher proportions of these materials did not show clear advantages in comprehensive evaluation, suggesting that they are better suited as supplementary rather than dominant substrate components. Yellow soil served as a basic component providing mineral nutrients and buffering capacity; however, excessive proportions increased bulk density and reduced aeration, which was unfavorable for seedling growth [52].

Overall, composite substrates based on yellow soil, supplemented with appropriate proportions of peat-based materials and inorganic porous components, were more conducive to coordinated growth and improved comprehensive quality of *Z. schneideriana* container seedlings.

4.4. Production Implications of the Synergistic Effects of Containers and Substrates

Based on the combined results of the individual trait analyses, principal component analysis, and comprehensive evaluation, container size appeared to be an important factor influencing container seedling cultivation of *Z. schneideriana*, while substrate formulation exerted an additional regulatory and enhancing effect on seedling growth performance. However, the comprehensive ranking was determined jointly by multiple traits, container type, and substrate formulation, rather than by pot size alone. This conclusion is consistent with the widely accepted concept of “container priority and substrate modulation” reported in studies on container-grown woody species [53,54].

In practical nursery production, although some treatments achieved higher comprehensive scores, factors such as material cost, availability, and environmental sustainability should also be considered. From the perspective of experimental performance, B-type containers generally showed better growth promotion and higher comprehensive scores under medium- and large-size conditions. Meanwhile, nonwoven fabric containers may still offer advantages in aeration and sustainability, and thus could be considered as an alternative option in practical nursery management [55]. Accordingly, for container cultivation of *Z. schneideriana*, large containers generally showed the most favorable overall performance, whereas the relative suitability of medium and small containers depended on the specific combinations of container type and substrate formulation. Lightweight composite substrates dominated by peat-based materials and appropriately supplemented with inorganic porous components may represent suitable cultivation options for achieving good seedling performance and practical nursery applicability.

5. Conclusions

(1) B-type containers generally exhibited better overall performance among container materials under medium- and large-size conditions.

Under identical container size and substrate conditions, container material influenced the growth and physiological traits of *Zelkova schneideriana* seedlings. Based on seedling height, ground diameter, biomass accumulation, and comprehensive evaluation results, B-type containers generally showed stronger growth-promoting effects and relatively higher comprehensive scores under medium- and large-size conditions. This suggests that container material affected seedling performance, and that B-type containers were more advantageous for vegetative growth and biomass accumulation under suitable size conditions.

(2) Large container sizes generally showed the most pronounced advantages.

Under identical container material and substrate conditions, increasing container size from small to medium and large generally enhanced vegetative growth, biomass accumulation, nutrient contents, photosynthetic traits, and root development. Principal component analysis and comprehensive evaluation suggested that small containers could limit overall seedling quality due to restricted root growth space, whereas large containers ranked highest for most traits and comprehensive scores. Medium containers exhibited variable performance depending on the specific combination of container type and substrate formulation. Therefore, large containers may be considered the most favorable size for *Z. schneideriana* container seedling production under the conditions of this study.

(3) The T₃ composite substrate was identified as the optimal substrate formulation.

Under identical container material and size conditions, substrate formulation significantly affected seedling growth, physiological traits, and root morphology. Treatments with the T₃ composite substrate consistently achieved higher comprehensive scores under most container conditions, demonstrating good stability and coordination among growth, photosynthesis, and root development. T₂, T₄, and T₅ showed moderate performance, whereas the control substrate performed relatively poorly. Accordingly, T₃ is recommended as the optimal substrate formulation for *Z. schneideriana* container seedling cultivation.

(4) Integrated analysis and recommended optimal cultivation schemes.

Based on single-factor analyses, principal component analysis, and comprehensive evaluation, container size was an important factor determining seedling quality, whereas container material and substrate formulation played regulatory and enhancing roles. The combination of appropriate medium-to-large container size and the T₃ composite substrate exhibited the best overall performance, while B-type containers generally showed superior performance among container materials under medium- and large-size conditions. According to the comprehensive evaluation, T₃/A₃ ranked first, followed by T₃/B₂. Medium containers combined with the same substrate and container material may still represent a feasible alternative under specific conditions, although their relative performance is dependent on the interaction between container type and substrate formulation.

(5) Future perspectives.

Future studies should evaluate the long-term performance of seedlings grown under these optimized container–substrate combinations, particularly after transplanting in field conditions. It will also be valuable to assess adaptability and survival stability under different environmental conditions. Further research could incorporate production cost, material accessibility, and management efficiency to improve practical applicability of container seedling cultivation systems.

6. Patents

The research reported in this manuscript has resulted in a related Chinese invention patent. The patent, entitled “A Method for Improving Seed Germination rate of *Zelkova schneideriana*”, has been filed with the China National Intellectual Property Administration (CNIPA). The patent application has been officially accepted and published. The applicant institutions include Hunan Academy of Forestry and Central South University of Forestry and Technology.

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Abbreviations

The following abbreviations are used in this manuscript:

APC	Article Processing Charge
ANOVA	Analysis of Variance
CK	Control Substrate
CNIPA	China National Intellectual Property Administration
Ci	Intercellular CO ₂ Concentration
Gs	Stomatal Conductance
N	Total Nitrogen
P	Total Phosphorus
K	Total Potassium
PCA	Principal Component Analysis
Pn	Net Photosynthetic Rate
SPSS	Statistical Package for the Social Sciences
T ₁ –T ₅	Different Substrate Treatments
TN	Total Nitrogen
TP	Total Phosphorus
TK	Total Potassium
Tr	Transpiration Rate

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