

Investigation of growth and photosynthetic traits across eighteen oak varieties to identify superior varieties for southwest China

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Abstract: *Quercus*, commonly known as oak, has great potential as one of the most widely plants. However, the lack of superior varieties is a bottleneck for its usage and application in Southwest China. Here, this study aims to explore the growth and photosynthetic traits of 18 oak varieties with the goal of identifying the adaptable superior varieties for the region, focusing on nutrient growth, leaf morphology, chlorophyll content, and photosynthetic parameters over a 32-week growth period. The results showed that a significant diversity was observed among the varieties. Growth rhythm and fitted curves can divided the 18 oak varieties into three patterns. Additionally, for the leaf morphological parameters, Qd boasted the maximum leaf area, leaf width, and leaf aspect ratio, Qm showed the greatest leaf length, while Qa had the largest leaf form factor and leaf gap. Chlorophyll content was based on three time-points investigation, with higher level observed in Qm, Qr4, Qw, Qd, Qa, and Qr1. The transpiration rate (E), stomatal conductance (gsw) and total water vapor conductance (gtw) were dominantly obtained in Qr1, while Qd exhibited the highest intercellular CO₂ concentration (Ci). Conversely, Qw displayed a significantly higher leaf chamber CO₂ concentration (Ca). Furthermore, growth traits showed the similar correlation with leaf morphological and photosynthetic traits. PCA analysis grouped the oak varieties into five clusters, Qa, Qr1, Qp3, Qd, Qn, Qm and Qw identified as superior varieties. These findings not only offer promising oak candidate varieties for Southwest China, but also provide insights for establishing efficient breeding program for other woody plants.

1 Introduction

Quercus, commonly referred to as oak, constitutes the largest group within the Fagaceae family and plays a pivotal role in forest ecosystem (Xiao-Yan et al., 2022). With around 400-600 species, oaks are found in temperate to tropical areas of Northern Hemisphere (Denk et al., 2017), holding significantly economic and ecological value. In China, particularly in southwest regions, approximately 120 oak species thrive in mountainous areas (Xingwang et al., 2015). Oaks fulfill diverse functions, contributing to wood and charcoal production, while also playing crucial roles in soil conservation and biodiversity preservation (Wenwen et al., 2023; Shuxia et al., 2020; Yaowu et al., 2013). However, oak candidate varieties in Southwest China encounter various challenges hindering their prosperity. Notably, the scarcity of superior types limits their practical application and utilization. Therefore, it is essential to investigate the growth and physiological attributes of oak species, serving as the scientific groundwork for effective utilizing and cultivating exceptional oak varieties in China.

Tree growth, a widely used metric for assessing plant performance, is also a crucial factor in determining forest productivity and biomass accumulation(Islem et al., 2019). Growth traits are integral for the survival of forest trees and influence intraspecific competition, particularly in economically significant tree species. These traits offer valuable insights into identifying optimal timings for by-product harvesting(Yuanzhi et al., 2024). Previous study had elucidated significant variations in growth rhythms concerning tree height and diameter at breast height (DBH) across diverse tree species(Akihiro, et al., 2013). Notably, many species exhibited seasonal growth pattern, with accelerated growth during spring, summer, or autumn, but slower growth during winter, indicating distinct growth strategies in response to seasonal changes(Filipe et al., 2023; Barbeta et al., 2012). Thus, environmental factors, such as temperature and precipitation, exerted considerable influence on tree growth rhythms(Wang, et al., 2016; Bingrui et al., 2021). Furthermore, recent study had highlighted the interactions between tree species and environmental conditions in shaping growth rhythms (Lavender, 1984), often associated with adaptive responses to local climate variations, soil composition and elevation(Gianluigi and Dimitrios, 2021). Moreover, previous studies have demonstrated that logistic models had been favored for modeling plant growth processes and have been extensively utilized in investigating seedling growth patterns(Camila et al., 2024; Yusheng et al., 2023). In sum, understanding the developmental rhythm patterns was crucial for cultivating superior tree species, improving afforestation survival rates, and determining optimal harvesting seasons(Md Aktar et al., 2023).

Leaves serve as the primary sites for photosynthesis in forest trees, harnessing energy for the ecosystem's primary producers(Yusheng&Zhonghua, 2023). Photosynthesis stands as a cornerstone biological process in forest trees, profoundly shaping their lifelong growth and development(Lina et al., 2019). By analyzing the photosynthetic and physiological variations of *C. oleifera* 'Huaxin' throughout the year, it becomes feasible to determine the optimal leave-to-fruit ratio for enhancing fruit productivity(Xiaoyan et al., 2023). Previous studies have demonstrated that leaf photosynthetic traits influenced transpiration regulation(Auobi and Behtash, 2020; F. Iniesta et al., 2009). In general, tree species with enhanced photosynthetic capabilities exhibited elevated transpiration rates(Giancarlo et al., 2014). A comparative analysis of the photosynthetic characteristics of regenerated European beech (*Fagus sylvatica*) and pedunculate oak (*Quercus robur*) plants offers valuable insights into the adaptation mechanisms and physiological roles of these broadleaf species(Emile et al., 2009). Additionally, leaf traits directly impact the forest trees' photosynthetic potential, with photosynthetic pigments within playing pivotal roles in the photosynthesis process(Yanting et al., 2023). Assessing chlorophyll content, a common practice in forestry and ecological studies, holds particularly significance in current research(Siyu et al., 2024). This assessment, often complemented by other leaf morphological and physiological parameters, facilitates comprehensive evaluations. Research has established a correlation between leaf chlorophyll concentration and plant health levels(Atkilt et al., 2013; Filippo et al., 2020). For instance, reduced chlorophyll concentration indicates decreased forest vitality(Hong et al., 2007). Therefore, monitoring chlorophyll levels in leaves provides a valuable means of accurately assessing the overall health of forest trees.

To date, previous studies have predominantly concentrated on tree breeding and stress resistance in oak species(Pedro G. et al.,2024; Xia et al.,2012).However, there remains a notable gap in research concerning the growth and physiological variability of different oak varieties. Furthermore, the current study lacks a comprehensive evaluation of a diverse range of oak cultivars, hindering a thorough examination of inter-variety differences and the development of superior varieties. Therefore, elucidating the growth and photosynthetic traits of oak trees represents an initial step in the cultivation and breeding process, offering a productive approach to fostering the advancement of superior variations within the production domain. Here, the aims of this study were as follow: 1) Collected 18 varieties of common oak seedlings from different countries and regions to investigate the growth traits as long as 32 weeks; 2) Evaluated the significant differences and correlation of the traits among different oaks, containing nutrient growth, leaf morphology index, chlorophyll content, and photosynthetic indexes; 3) Preliminary screened the superior materials to Southwest China. This data will provide a support information to breed superior oak varieties in Southwest China, and contribute more references associated with plant growth traits of oaks for the other regions.

2 Materials and Methods

3 Study site information

The study was performed in the Forestry base of Sichuan Agricultural University, which located at Wenjiang District, Chengdu City, Sichuan Province (30°72'N, 103°93'E). The average elevation was 511 m, and the soil types of the nursery site was a 5:1 mixture of local soil and Hogwarts brand plant nutrient organic soil. The climate here is humid subtropical, with an average annual temperature of 22°C, four distinct seasons, mild climate, and abundant rainfall(Chen et al.,2022).

4 Experimental material information

The oak seedlings of two or three years old were selected to perform this study. All the seedlings were planted in the pots with about 1 m in diameter to provide ample growing space, and the nutrient soil was mixed with local soil (50:50) for cultivating the seedlings(Jiangtao et al.,2022).The information of 18 selected oak varieties were shown in **Table 1**.

Table 1. The origin information of 18 oak varieties in this study

No.	Oak variety name	Origin	Abbreviation
1	<i>Quercus lyrata</i>	Henan, China	Ql
2	<i>Quercus acutissima</i> Carruth.	Shandong, China	Qa
3	<i>Quercus coccinea</i> Muench	Shandong, China	Qc
4	<i>Quercus dentata</i> Thunb.	Shandong, China	Qd
5	<i>Quercus mongolica</i> Fisch. ex Ledeb.	Shandong, China	Qm
6	<i>Quercus nuttallii</i>	Chongqing, China	Qn
7	<i>Quercus palustris</i> Münchh.	Shandong, China	Qp0
8	<i>Quercus palustris</i> Münchh. (No.1)	Shandong, China	Qp1
9	<i>Quercus palustris</i> Münchh. (No.2)	Shandong, China	Qp2

10	<i>Quercus palustris</i> Münchh. (No.3)	Shandong, China	Qp3
11	<i>Quercus robur</i> L. (Shandong)	Shandong, China	Qr1
12	<i>Quercus robur</i> L. (England)	England, UK	Qr2
13	<i>Quercus robur</i> L.	Helsinki, Finland	Qr3
14	<i>Quercus robur</i> L.	Xinjiang, China	Qr4
15	<i>Quercus robur</i> x <i>bicolor</i> 'Nadler'	Shandong, China	Qrb
16	<i>Quercus rubra</i> L. (Shandong No.1)	Shandong, China	Qru1
17	<i>Quercus rubra</i> L. (Shandong No.2)	Shandong, China	Qru2
18	<i>Quercus wutaishansea</i> Mary	Shandong, China	Qw

5 Growing traits measurement

Five well-grown seedlings were respectively selected from each of 18 oak varieties for height and diameter measurements, which were conducted approximately every two weeks, starting from March 09, 2023 until October 20, 2023. In this study, the seedling height and ground diameter were investigated as the key growing traits of each oak. Seedling height refers to the vertical height of oak seedlings(De Petris et al.,2022), and the height of the above ground portion of the plant was measured with a tape measure(Ying et al.,2019). Ground diameters at a height of 3-5 cm from the soil surface were taken twice and averaged to obtain the precise data using vernier calipers.

6 Leaf morphometric determination

During the peak growing season of oak trees, On July 30, 2023, three mature leaves were randomly sampled from each oak tree. A total of six leaf morphology parameters were measured using a leaf area meter survey, containing leaf length, leaf width, leaf area, leaf aspect ratio, leaf form factor, and leaf gap(Martin et al.,2020). Every leaf underwent three measurements. Subsequently, statistically analysis was conducted to evaluate the variation in leaf morphology among the different oak varieties.

7 Photosynthesis parameter investigation

Eleven candidate oak varieties were selected for photosynthesis parameters investigation based on their superior growth characteristics. In totally, six traits were weekly investigated from July 19 to August 30, 2023, during clear weather, between 9:30 a.m. and 12:30 p.m. All the parameters were detected using a portable photosynthesizer, LI-6800 (LI-COR, Inc., USA) positioned in the middle section of the plant canopy, including transpiration rate (E), intercellular CO₂ concentration (Ci), leaf chamber CO₂ concentration (Ca), stomatal conductance (gsw), and total water vapor conductance (gtw) of the mature functional leaves(Alejandro et al.,2021).The reference chamber CO₂ concentration was set at 400 µmol/mol, with leaf chamber temperature set to 30 °C and a relative humidity of 50%. Light intensity was maintained to match ambient conditions at 1000 µmol m⁻²s⁻¹. The leaves were selected from the same orientation as the mature functional leaves(Ábri et al.,2023).Measurements were conducted on three plants per treatment, with three leaves sampled from each plant.

8 Chlorophyll content investigation

In July 16, July 31, and August 16, 2023, the mature and healthy leaves of similar location were respectively collected from the 11 candidate oak varieties in the middle of the canopy.In each investigation, three leaves were

sampled and weighed for each variety, and the total chlorophyll content was determined by chlorophyll meter(Weidong et al.,2024).

9 Statistical analysis

Data were statistically processed and analyzed using Excel 2018 and SPSS Statistics 24.0, Origin 2018 was employed to draw the figures(Iman S et al.,2024).One-way analysis of variance (ANOVA) and least significant difference (LSD) tests were performed to assess variance among the samples of oaks growth and photosynthesis, presented in mean with standard error of the mean ($\text{Mean} \pm \text{SEM}$)(Xiao-Jun et al.,2008).Pearson's correlation analysis was utilized to estimate correlation coefficients and relationships between growth, leaf and photosynthesis traits. Principal component analysis (PCA) was conduct to evaluate the oak candidate varieties and identify the superior members.

10 Results

11 Growth traits investigation of the 18 oak trees

Growth traits play a crucial role in forests evaluation, serving as indicators of stand productivity and facilitating predictions of overall growth and succession(Jing-Ming et al.,2022).The seedling height and ground diameter of the 18 oak trees exhibit similar growth patterns, characterized by distinctive "S"-shaped curves (**Fig.1**).However, notable differences emerged during their developmental stages. Seedling height experiences an initial growth phase from May to early June, followed by a rapid growth period from mid-June to late July, and a subsequent tapering of growth from August to early October, ceasing altogether by mid-October (**Fig. 1a**). In contrast, ground diameter showed early growth from June to early July, followed by a rapid growth period from mid-July to mid-August, and a gradual tapering of growth from late August to late October(**Fig. 1b**).

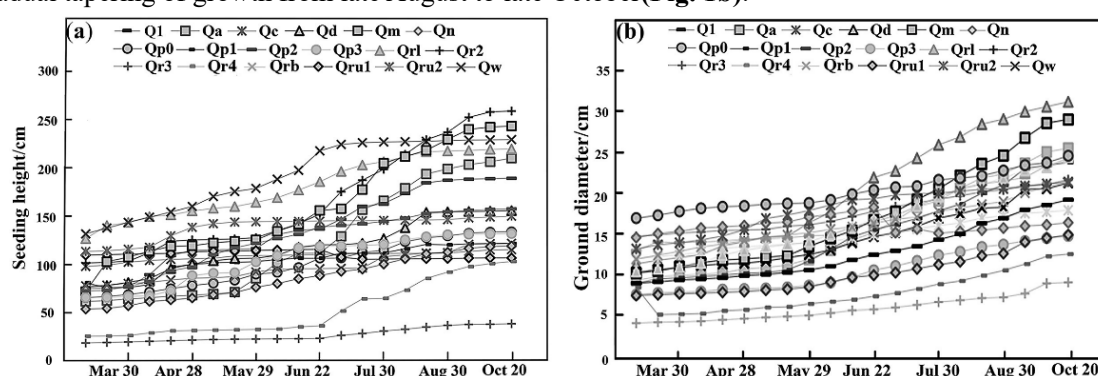


Figure 1. The average growth patterns of seedling height (a) and ground diameter (b) across the annual growing season for 18 oak varieties.

12 Growth patterns analysis of the 18 oak trees

The net increase in seedling growth serves as a reliable foundation for evaluating their growth rate. Understanding the growth patterns of oak trees can lay a theoretical basis for scientific management and cultivation(Sprengel et al. 2018).This study discovered a consistent developmental pattern in the net rise of seedling height and ground diameter of oaks throughout the annual growing season.While both measurements can be

classified into three groups, there may be slight variations among different individuals.

The height growth patterns of 18 oak seedlings were divided into three types, including H-I, H-II, and H-III types (**Fig.2, Fig.S1**). In the H-I type, oaks exhibited biannual growth periods, with the most substantial growth between spring and summer, particularly in June-August, characterized by vigorous growth (**Fig.2a-b, Fig.S1a-d**). Therefore, it is crucial to fertilize the oak trees during this period to ensure their development. Additionally, Oak trees of H-II type exhibited three growth periods annually, primarily in March, June, and August (**Fig.2c-d, Fig.S1e-h**). Growth in this type may be impeded by rainfall or high temperatures, possibly explaining the slowed growth observed in May and July. Finally, the H-III type oak trees thrived predominantly in the first half of the year (**Fig.2e-f, Fig.S1i-l**), specifically from March to May, with a significant slowdown in height growth during the latter half of the year. Thus, it is essential to apply adequate fertilizers and ensure nutrient availability during the spring growth period.

Similarly, the ground diameter growth patterns of 18 oak seedlings could also be divided into three types, including D-I, D-II, and D-III types (**Fig.3, Fig.S2**). In the D-I types, oaks exhibited steadily and continuously growth periods, particularly in Summer-Autumn (**Fig.3a-b, Fig.S3a-c**). Hence, it is vital to timely administer fertilizer during this period to ensure the oak trees receive adequate nutrients. Moreover, oak trees growth of D-II type exhibited fluctuated dramatically throughout the investigated months (**Fig.3c-d, Fig.S3d-k**). Finally, the D-III type oak trees exhibited two rapid-growth phases, in May-June and August-September, respectively. Therefore, it is advisable to apply fertilizer and watering promptly during this period in oak trees to ensure their strong and consistent development.

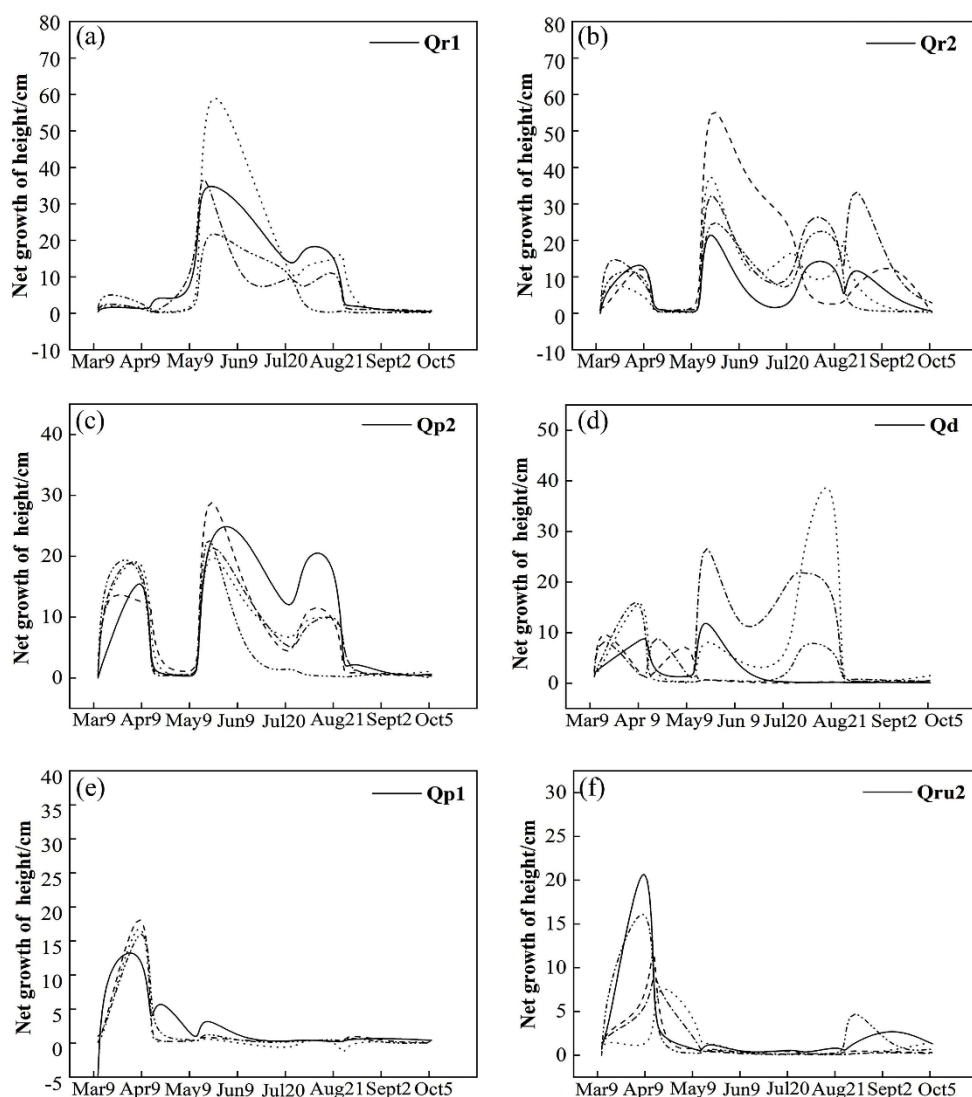


Figure 2. Primary patterns of growth rhythm in oak seedling height across the annual growing season in this study. a-b are the representative varieties in Pattern H-I: two growth periods mainly in spring and summer, especially from June to August with vigorous growth; e-d are the representative varieties in Pattern H-II: the three distinct growth periods occurring in March, June, and August. Growth significantly slows during the periods of heavy rainfall and high temperatures. e-f are the representative varieties in Pattern H-III: rapid growth in the first half of the year around March to May. Different lines mean the individual trees investigated in each variety.

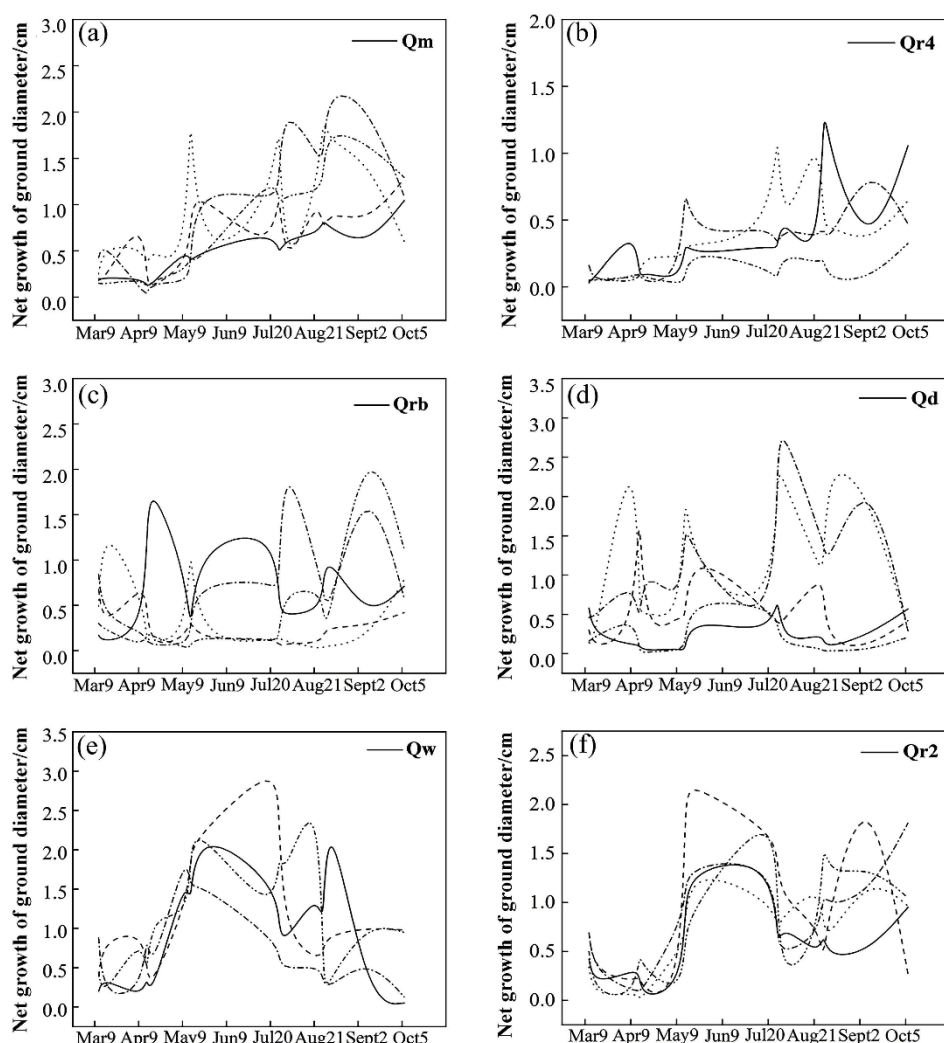


Figure 3. Primary patterns of growth rhythm in oak ground diameter across the annual growing season in this study. a-b are the representative varieties in Pattern D-I: consistent growth throughout the investigated months, notably with rapid growth from summer to autumn; c-d are the representative varieties in Pattern D-II: a fluctuating growth throughout the investigated months; e-f are the representative varieties in Pattern D-III: two rapid growth periods, respectively from May to June and August to September. Different lines mean the individual trees investigated in each variety.

13 Growth curve fitting of the 18 oak trees

The growth curves of oak trees were modeled using the Logistic equation employing observed values of oak growth traits. The R^2 values for all oak trees, except Qru1, exceeded 0.9, indicating an excellent fit of the Logistic model and a highly significant correlation across these varieties. Each oak variety displayed distinct S-shaped fitted curves, offering valuable insights into their growth patterns and predictive capabilities.

The height of seedlings can be classified into three patterns based on the onset of tachyphylaxis in different oak trees (**Fig.4a-c, Fig.S3**). The first pattern, labeled as Qd (**Fig.4a**), demonstrates a pronounced period of rapid growth that persists for an extended duration, exhibiting nearly uninterrupted expansion throughout the analyzed timeframe. The second growth phase, represented by Qm (**Fig.4b**), initiates after 60 days of growth and undergoes a period of rapid increase. This growth is sustained for a certain duration before gradually declining, indicating

eventual stagnation. The third pattern, known as Qru2 (**Fig.4c**), begins its rapid growth phase at an earlier stage when the seedling is 30 days old. However, this phase is shorter in duration, after which the growth rate gradually decreases until it stops completely.

While the ground diameter fitting curves of most oak trees exhibit similarities, they can be classified into three distinct groups based on the slope of the curves (**Fig.4d-f, Fig.S4**). The first category, exemplified by Qd (**Fig.4d**), displayed a consistent pattern of continuous expansion, characterized by a gentle slope and a steady rate of growth. The second category, illustrated by the Qw (**Fig.4e**), is marked by a "slow-fast-slow" growth pattern. After 80 days, they transitioned into a phase of rapid growth, which persisted for a specific duration before gradually diminished. In the third category, such as Qru2 (**Fig.4f**), the oak trees entered a fast-growth phase around 30 days, although this phase was short-lived. Subsequently, the rate of growth gradually declined, resulting in a plateau stage.

Overall, the rapid development phase of oak seedlings, comprising approximately 40% or more of the entire growth cycle, holds a crucial role in oak tree growth. This period exerts a significant influence on the overall growth trajectory of the seedlings. Therefore, it is imperative to optimize water and fertilizer management as the seedlings approach this phase of rapid growth. Timely application of fertilizer is essential to ensure that the seedlings receive sufficient nutrients for their rapid development.

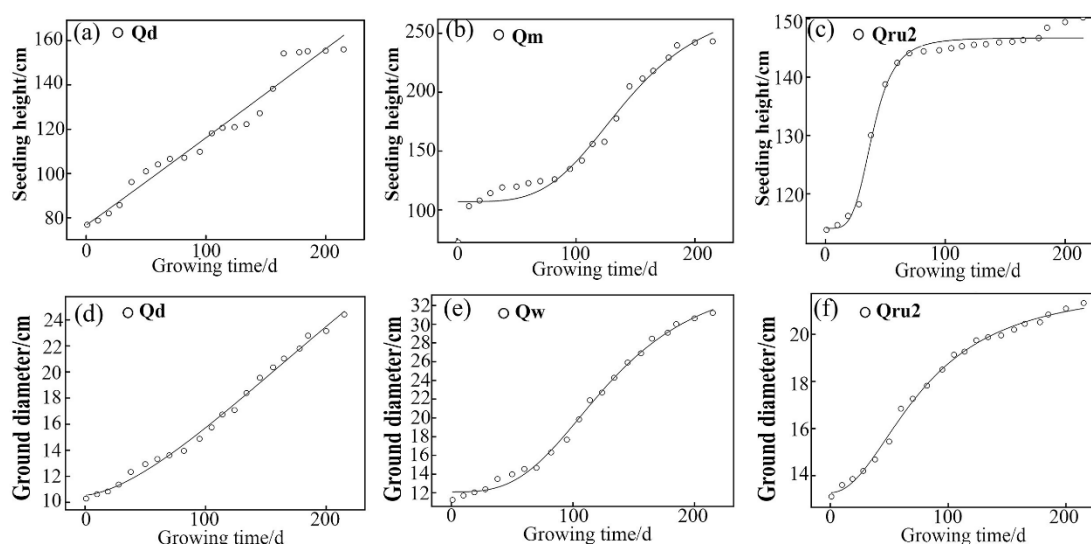


Figure 4. Fitted curve of dynamic growth related to oak seedling height and ground diameter. a-c: three mainly patterns of fitted curves for oak seedling height. d-f: three mainly patterns of fitted curves for oak ground diameter. All fitted curves were estimated based on the 200 days investigation.

14 Leaf morphological investigation of the 18 oak trees

Leaves play a vital role in regulating the plant growth. This study investigates the leaf morphological traits of 18 oak varieties to gain deeper insights into the factors influencing variations in their growth. Our phenotypic observations revealed significant differences in oak leaf morphology (**Fig.5**). While further findings suggest that, the significant variation was observed in the leaf morphology indices among different oaks (**Fig.6**). Qd demonstrated

the highest values for leaf area, leaf width, and leaf aspect ratio, while Qm showed the largest leaf length, suggesting their robust leaf development, which augments photosynthetic capacity (**Fig.6a, Fig.6c-d**). Conversely, Qc and Qr3 exhibited lower values across these indices, suggesting suboptimal leaf growth, thereby impacting the photosynthetic capacity adversely (**Fig.6a, Fig.6c-d**). Furthermore, in terms of leaf form factor and leaf gap, Qa exhibited the highest value, indicating its superior capacity to enhance transpiration and photosynthesis by enlarging stomata (**Fig.6e-f**).

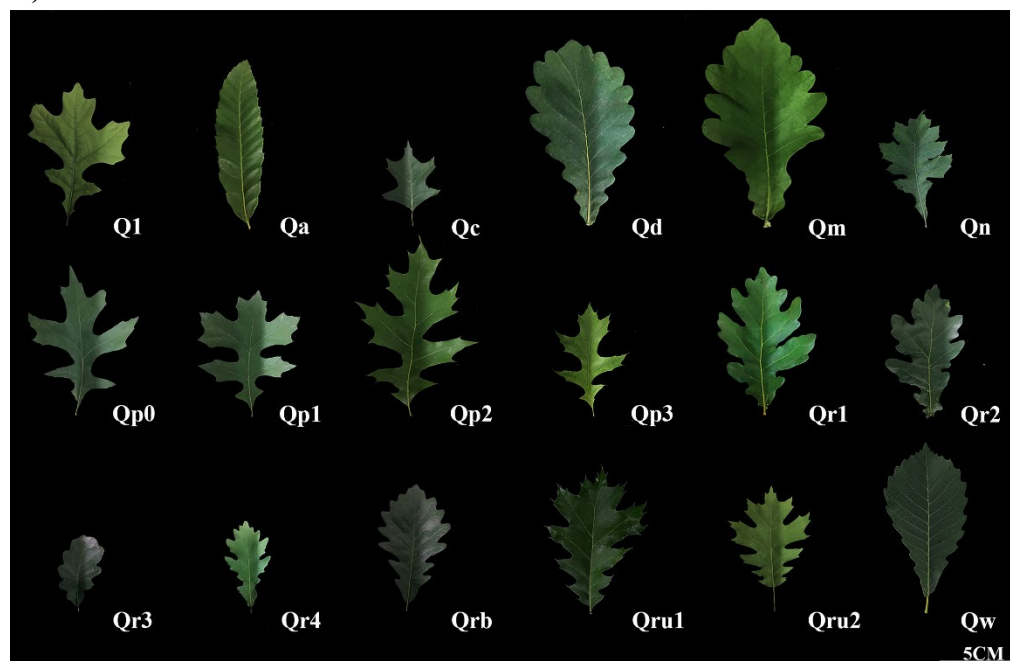


Figure 5. Leaf phenotypes of 18 different oak varieties. The bar is 5cm.

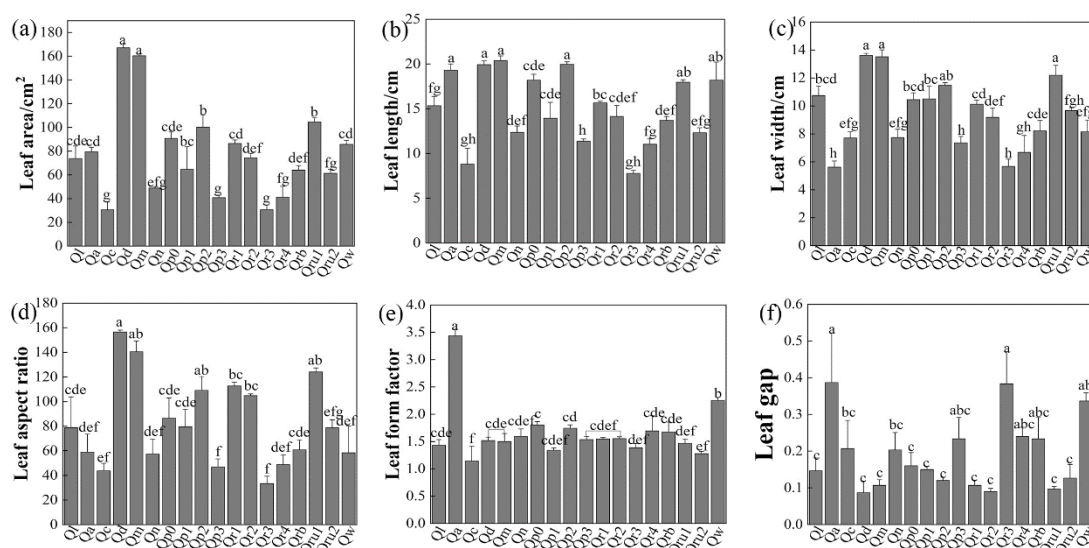


Figure 6. Leaf morphological investigation and analysis in 18 oak varieties. Different lower-case letters indicate significant differences among different varieties, $p < 0.05$.

15 Photosynthetic traits investigation of the 18 oak trees

Based on the above growth traits investigation and analysis, we selected 11 oak varieties to uncover the patterns of photosynthetic traits, including Q1, Qa, Qd, Qm, Qn, Qp3, Qr1, Qr4, Qrb, Qru2 and Qw.

Chloroplast pigments serve as the fundamental components for photosynthesis in forest trees, and the fluctuation in chlorophyll content indicates the photosynthetic capacity of forest trees(Wei et al.,2024). Significant differences in chlorophyll content were observed among the 11 oak varieties (**Fig.7a, Table S1.**).On 16th July, Qr4 exhibited the highest chlorophyll content, surpassing Qn by 77.99%. By 30th July, while Qn still retained the lowest chlorophyll content, Qm emerged with the highest value, representing a 76.65% increase. On 16th August, Qr1 displayed the highest chlorophyll content, surpassing Qn by 82.12%. The collective findings from the 3-day survey reveal that Qm, Qr4, Qw, Qd, Qa, and Qr1 consistently maintained high chlorophyll levels, suggesting their superior photosynthesis potential. Conversely, Qn and Qru2 exhibited consistently low chlorophyll content, suggesting a diminished photosynthetic capacity.

Significance variations in photosynthetic traits were observed among the 11 oak varieties (**Fig. 7b-f, Table S1.**). Qr1 exhibited the highest transpiration rate (E), stomatal conductance (gsw), and total water vapor conductance (gtw) indicating a superior photosynthetic capacity. These values were found to be 86.35% , 61.71% and 76.72% respectively higher than the lowest values recorded in Qr4 (**Fig.7b, Fig.7e, Fig.7f**). Qd exhibited the highest intercellular CO₂ concentration (Ci), surpassing Qp3 by 60.09% (Fig.7c). Conversely, Qw displayed a significantly higher leaf chamber CO₂ concentration (Ca) compared to the other oak varieties, with a relative increase of 40.17% compared to the lowest recorded in Qp3 (**Fig.7d**). However, little significant difference between the this indicator among other oak varieties.

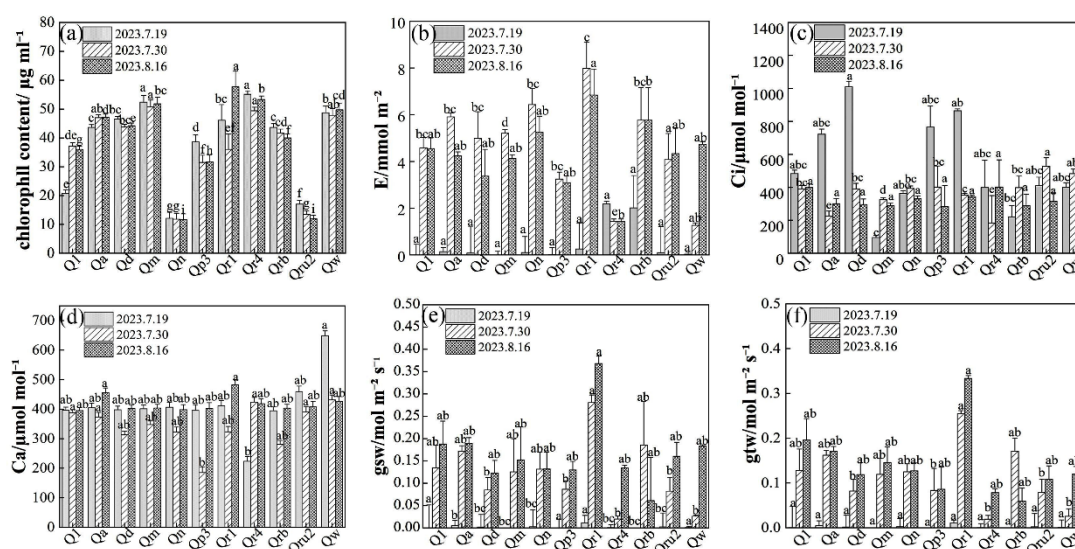


Figure 7. Analysis of photosynthetic parameters for 11 oak candidates. Different low-case letters indicated significant differences among the 11 oak candidates, $p < 0.05$. E: the transpiration rate, Ci: intercellular CO₂ concentration, Ca: leaf chamber CO₂ concentration, gsw: stomatal conductance, gtw: total vapour conductance.

16 Correlation analysis of growth and photosynthetic traits

A Pearson's correlation analysis was conducted to elucidate the relationship between growth and photosynthetic traits (**Fig.8, TableS2.**). Seedling height showed a significant positive correlation with E, gsw, and gtw ($p < 0.05$), while ground diameter was positive correlation with chlorophyll content, leaf area, and leaf length ($p < 0.05$). Furthermore, a very significant positive correlation was observed among leaf length, leaf width, leaf area, and leaf aspect ratio ($p < 0.05$), whereas negative correlation were evident in leaf form factor, leaf aspect ratio, leaf gap, and leaf width ($p < 0.05$). Moreover, most photosynthetic traits showed negative correlations, except for those among gtw, gsw, and E, indicating that stomatal conductance adjustment is essential to sustain the total water equilibrium and to ensure optimal photosynthesis in forest tree.

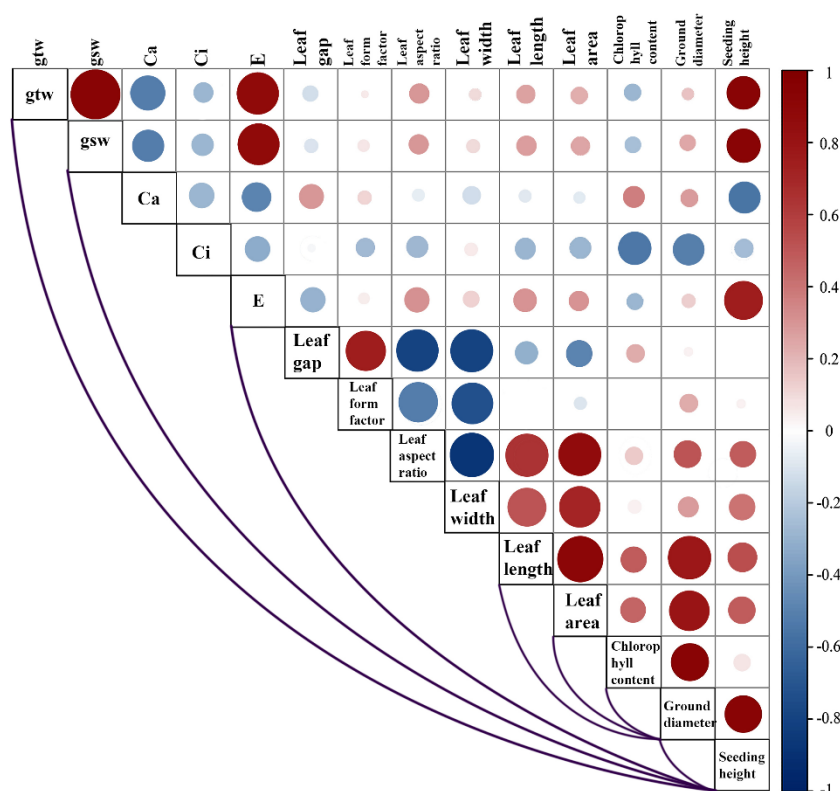


Figure 8. Correlation analysis between different traits investigated from 11 selected oak candidates. Red and blue indicate the positive and negative correlations, respectively. The darker color indicates more significant correlation between the traits ($p < 0.05$), and the size of the pies represent the correlation coefficient. The lines respectively highlight the significant correlation with seedling height and ground diameter, purple is positive correlation.

17 Comprehensive evaluation of oak varieties

Based on the correlation analysis, eight traits were selected to conduct principal component analysis (**Table.S3**), including ground diameter, seedling height, leaf length, leaf area, E, chlorophyll content, gsw, and gtw. The first two principal components contributed variance rates of 42.30% and 26.61%, respectively, totaling 68.91%, signifying their ability to encapsulate the majority of the information from the original eight indexes (**Table.2**). Consequently, these two primary components were selected for a comprehensive evaluation of the 11 oak varieties. Furthermore, the eigenvalues of the two principal components were 3.384 and 2.129, respectively (**Table.2**). The most significant contributors to PC1 are seedling height (X2) and E (X4), with contribution rates of 0.452 and 0.479

respectively (**Table.S3**). Conversely, in PC2, leaf length (X5) and leaf area (X6) emerged as the primary contributors, with contribution rates of 0.620 and 0.651, respectively (**Table.S3**). All these traits play pivotal roles in oak growth and can be used to conduct a comprehensive evaluation.

The ratio of the single PC contribution rate to the cumulative contribution rate was used as the weight for calculating the comprehensive evaluation scores of different oak varieties. The final evaluation scores of the 11 oak varieties were ranked as follows: Qa>Qn>Qw>Qm>Qr1>Qp3 >Qd>Qr4>Qrb>Ql>Qru2 (**Table.3**). In the loading plots (**Fig.9**), Qa achieved the highest composite score, indicating its superior adaptation to the climatic conditions in Southwest China. Conversely, Qrb, Ql and Qru2 obtained lower composite scores, indicating their unsuitability for cultivation in Southwest China due to inferior adaptability. Qm and Qw attained the highest overall scores after Qa, suggesting their potential for cultivation and favorable suitability. However, Qn exhibited a significantly higher PC1 value than PC2, indicating superior seedling height and transpiration rate, while Qr4 displayed a slightly higher PC2 value, suggesting robust leaf length and leaf area growth. Despite this, the composite score of Qn was 57.10% higher than that of Qr4, implying its superior adaptability and overall score. Additionally, Qr1, Qp3 and Qd, located at the centre of the plot, made more average contributions, with composite scores ranking in the upper range. This suggests their growth potential and adaptability to the cultivating environments in Southwest China. To sum up, Qa, Qr1, Qp3, and Qd, along with Qn, Qm and Qw, can be considered ideal candidates for cultivating superior oak varieties in further studies.

Table 2. The results of principal component analysis among 11 oak candidates

Principal Component	Eigenvalue	Percentage of Variance (%)	Cumulative (%)
Principal component 1	3.384	42.299	42.299
Principal component 2	2.129	26.608	68.907
Principal component 3	1.037	12.962	81.869
Principal component 4	0.575	7.191	89.060
Principal component 5	0.526	6.576	95.636
Principal component 6	0.263	3.283	98.919
Principal component 7	0.062	0.780	99.699
Principal component 8	0.024	0.301	100

Table 3. Comprehensive evaluation of growth and photosynthetic traits of 11 oak candidates

Species	Principal component value			Rank
	PC1	PC2	Total score	
Qa	2.056	0.517	1.007	1
Qn	2.312	-0.459	0.856	2
Qw	0.865	-0.160	0.324	3
Qm	0.943	-0.708	0.211	4
Qr1	-0.015	0.312	0.077	5
Qp3	0.865	-0.160	0.324	6
Qd	0.085	-0.538	-0.108	7
Qr4	-1.528	0.656	-0.472	8
Qrb	-0.564	-0.823	-0.457	9
Ql	-0.891	-0.426	-0.490	10
Qru2	-0.665	-1.447	-0.666	11

Total score is calculated by summing the product of the percentage of variance and the principal component value, eg: total score of Qa = 42.299%×2.056 + 26.608%×0.517≈1.007

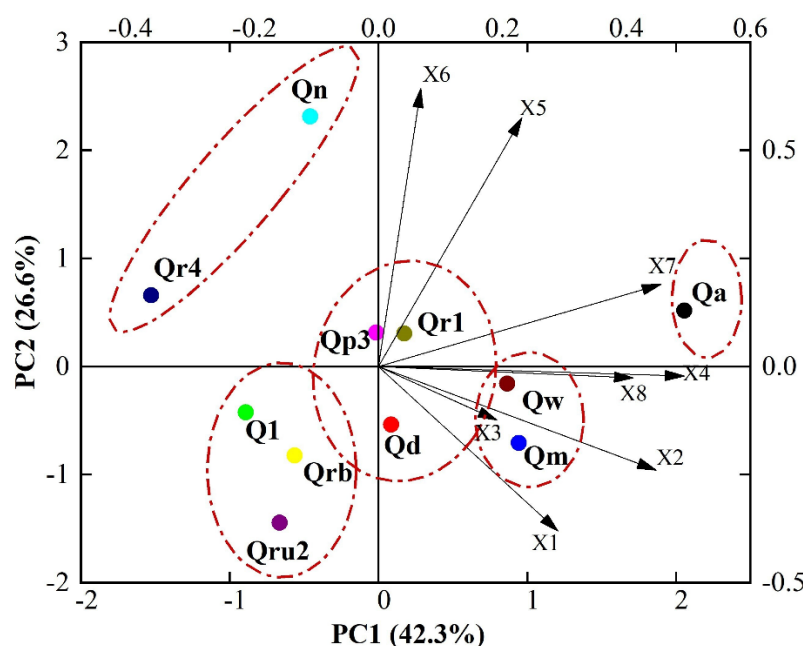


Figure 9. Principal component analysis to identify excellent varieties from 11 selected oak candidates. PC1 and PC2 were principal component 1 and principal component 2, X1-X8 were the loading score of various investigated traits. Different color pies showed the distribution of 11 oak candidates which were divided by the red circles.

18 Discussion

Forest growth encompasses a set of core attributes potentially influencing the survival, growth and mortality of forest trees, indicating their adaptive responses to the environment (Paul et al. 2012). Variations in growth traits among various oak species has been observed in several studies (Teresa et al. 2021; Teruyoshi and Kato. 2021), reflecting differences in initial habitats, experimental locations, and the inherent adaptability of oak trees. In this study, we found a significant association ($R^2 > 0.9$) between seedling height, ground diameter and predicted growth value, aligning with a “slow-fast-slow” in the “S” growth curve pattern. Similar results have been reported in other species, such as in *Morus* spp. (Rukmangada et al. 2020) and Chinese fir. (Li and Akio, 2001). Our results found that height and diameter of oak trees increased consistently from April to August, crucial for optimizing growing conditions and maximizing light absorption during Initial growth stages (Sprengel et al. 2018). Rapid height attainment during the seedling’s initial growth stages is essential for securing a favorable environment and subsequent development. Following a period of pre-development, significant nutrient accumulation primes seedlings for rapid growth (Barbeta et al., 2012). Despite the rapid growth phase of several oak trees constituting less than 2/5 of the developmental stage, it contributed to more than half of the total growth volume, underscoring its vital role in oak tree growth. However, this study noted an uneven growth pattern between height and diameter, common among closely related oak species (Teresa et al. 2021) likely due to long-term competition for survival (Fen et al. 2021). The pre-growth phase of seedling favors sunlight capture and space acquisition, while later phases denote lignification and bud formation (Md, Aktar. et al. 2023). Tailored management strategies, prioritizing water and fertilizer management during the seedling’s vertical growth phase, are crucial for stimulating accelerated growth and ensuring seedling quality. Extensive fertilizer application during later stages could further bolster plant resistance and enhance stand quality (Lichao et al. 2024).

Photosynthesis is a crucial aspect of forest tree growth and serves as a significant indicator of its capacity to adapt to the environment(Xiaoyan et al. 2023).Oak trees, being photophilous plants, rely on an adequate amount of sunlight to accumulate nutrients(Xingwang et al. 2015). Therefore, the photosynthetic traits of oak trees take an integral part in their successful transition in southwest China(Wenwen et al.2023). Among the several oak species studied, there was a substantial correlation between the growth, physiological traits, this was confirmed in this study(Iman, S. et al. 2024).We found that increased stomatal conductance (gsw) strongly and positively correlate with higher transpiration rate(E), which is consistent with previous findings(Qiulong et al. 2020). In this study, Qr1 had the highest values of E and gsw, indicating their self-regulation and superior photosynthetic capacity at the ambient condition. Chlorophyll content is closely related to photosynthesis since chlorophyll provides the photosynthetic apparatus that allows plants to absorb light energy in a time-efficient manner(Peiling et al. 2023). Our study revealed that Qm, Qr4, Qw, Qd, Qa, and Qr1 consistently maintained high chlorophyll levels, suggesting their superior photosynthesis potential. Overall, the current study showed that differences in photosynthetic traits could be attributed to other factors such as number and density of stomata, concentration of CO₂ in the atmosphere, etc(Aili et al. 2023). However, our findings suggest that the variations in growth traits were more greater than the photosynthetic traits among the oaks. For instance, altho owth, leaf morphological traits (e.g., leaf area and leaf gap) also differed significantly in many cases. A previous study found differential responses between different varieties of *Camellia sinensi*(Xiaoyan et al. 2023).This seems to imply that growth traits may be the first to be noticed and selected for in the selection and cultivation process of superior oak varieties.

Principal component analysis is a statistical tool used to explain differences between samples and obtain more information about variable, leading to a better understanding and assessment of the samples(Cícero et al. 2020).It simplifies complex work and provides more accurate results(Marcos et al. 2020). PCA has been widely employed in the adaptive investigation of various forest trees in different regions, such as Douglas-fir(et al. 2021), *Picea abies* (L.) H. Kars(Terhonen, et al. 2013).. In our study, we used PCA to analyze the growth and photosynthetic traits of 11 important oak species, effectively evaluating how well they adapt to the local environment. For oak varieties with high comprehensive adaptability (e.g. Qa, Qw, Qm), we could consider breeding them to maximize their benefits. Additionally, for varieties excelling in specific traits (e.g. Qn and Qd), we might explore hybridization to creat varieties with greater adaptability. Additionally, PCA results can help prioritize oak growth efforts and guide varietal enhancement towards emphasizing key traits.

This study focused on analyzing the growth and physiological traits of oak seedlings. Nutritional growth, leaf morphology, chlorophyll content and photosynthetic traits of different oaks were analysed for significance over a 32-week growth period, and combined with PCA to comprehensively assess and select superior varieties adapted to the region.However, it's important to note that our study was conduct in the Chengdu region, suggesting that the superior oak candidates identified in this study may be particularly suitable for this specific area. Nevertheless, more

different geographic conditions, such as climate, altitude, soil properties, could also be carried out in the further studies to enrich our understanding of oak breeding. Moreover, efforts to collect new germplasm resources could facilitate more detailed investigated, ultimately contributing to the cultivation of superior-quality oaks in Southwest China.

19 Conclusion

This study investigated significant variations in the growth and physiological traits of several oak varieties. Qr1, Qm, and Qw exhibited substantial growth advantages, although Qm and Qa shown greater dominance in leaf shape, and Qr1, Qa, Qm, and Qr4 displayed advantages in chlorophyll content. The transpiration rate (E), stomatal conductance (gsw) and total water vapour conductance (gtw) were highest in Qr1, while intercellular CO₂ concentration (Ci) was highest in Qd, instead, Qw displayed a significantly higher leaf chamber CO₂ concentration (Ca). When combined with principal component analysis, Qa, Qr1, Qp3, and Qd, along with Qn, Qm and Qw, are more suitable for the high summer temperatures and low rainfall. The findings of this study highlighted that it can be utilised to identify superior oak species that are ideally suited for local cultivation. This selection process has the potential to enhance both growth and photosynthetic traits simultaneously, with implications on the economic viability and sustainability of oak stands.

Acknowledgments

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Supplementary Material

Supplementary Figures

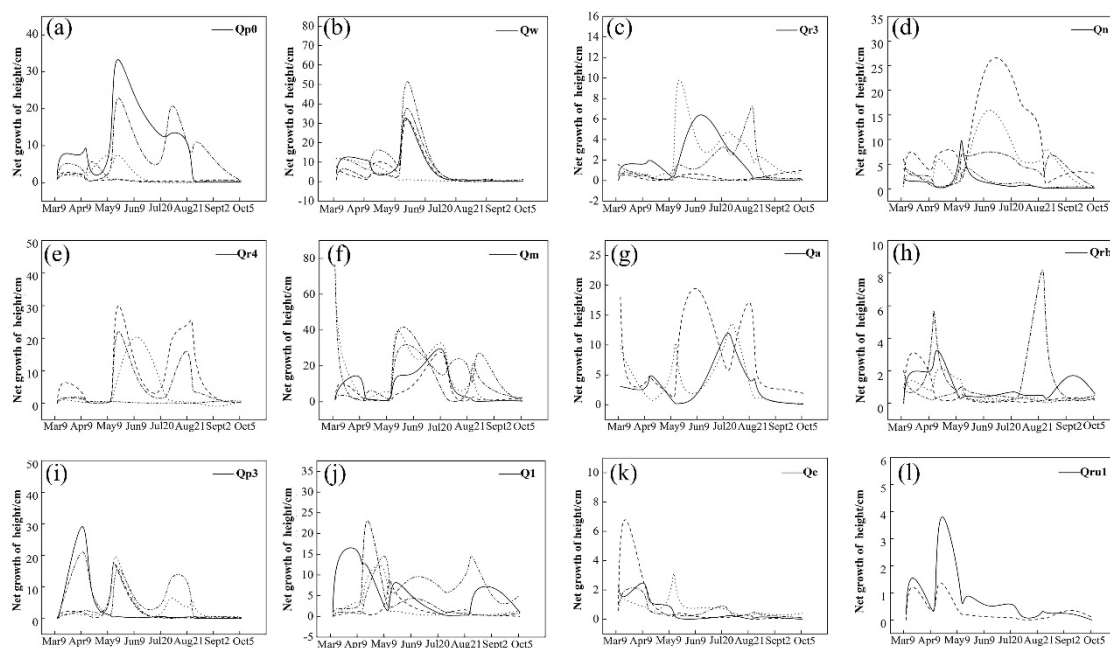


Figure S1. Primary patterns of growth rhythm in oak seedling height across the annual growing season in this study. a-d are the representative varieties in Pattern H-I: two growth periods mainly in spring and summer, especially from June to August with vigorous growth; e-g are the representative varieties in Pattern H-II: the three distinct growth periods occurring in March, June, and August. Growth significantly slows during the periods of heavy rainfall and high temperatures. k-l are the representative varieties in Pattern H-III: rapid growth in the first half of the year around March to May. Different lines mean the individual trees investigated in each variety.

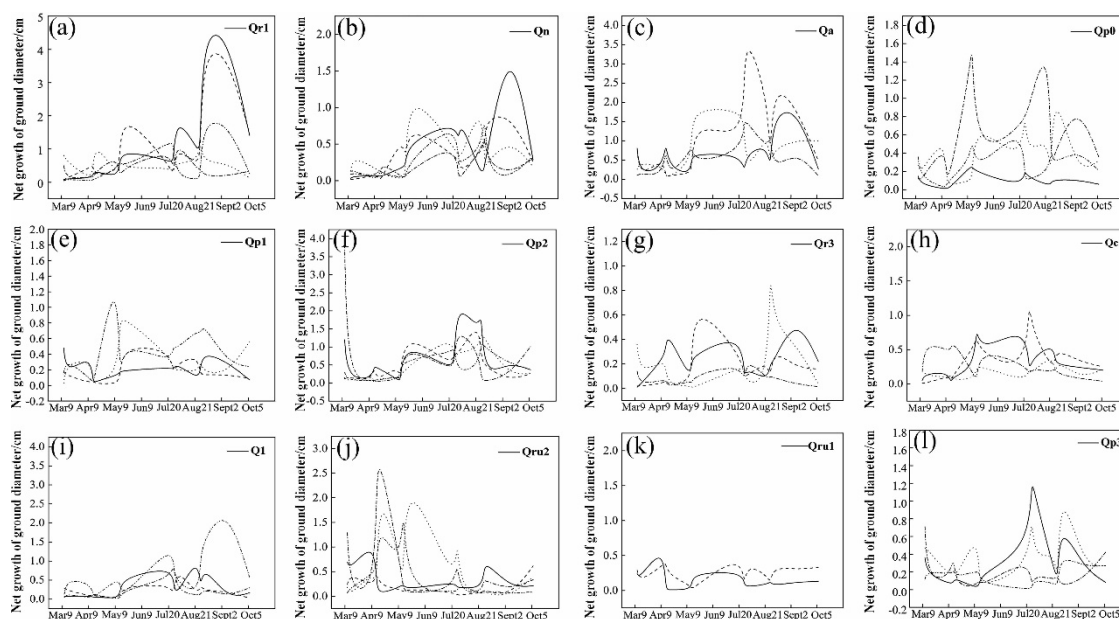


Figure S2. Primary patterns of growth rhythm in oak ground diameter across the annual growing season in this study. a-c are the representative varieties in Pattern D-I: consistent growth throughout the investigated months, notably with rapid growth from summer to autumn. d-k are the representative varieties in Pattern D-II: a fluctuating growth throughout the investigated months. l is the representative varieties in Pattern D-III: two rapid growth periods, respectively from May to June and August to September. Different lines mean the individual trees investigated in each variety.

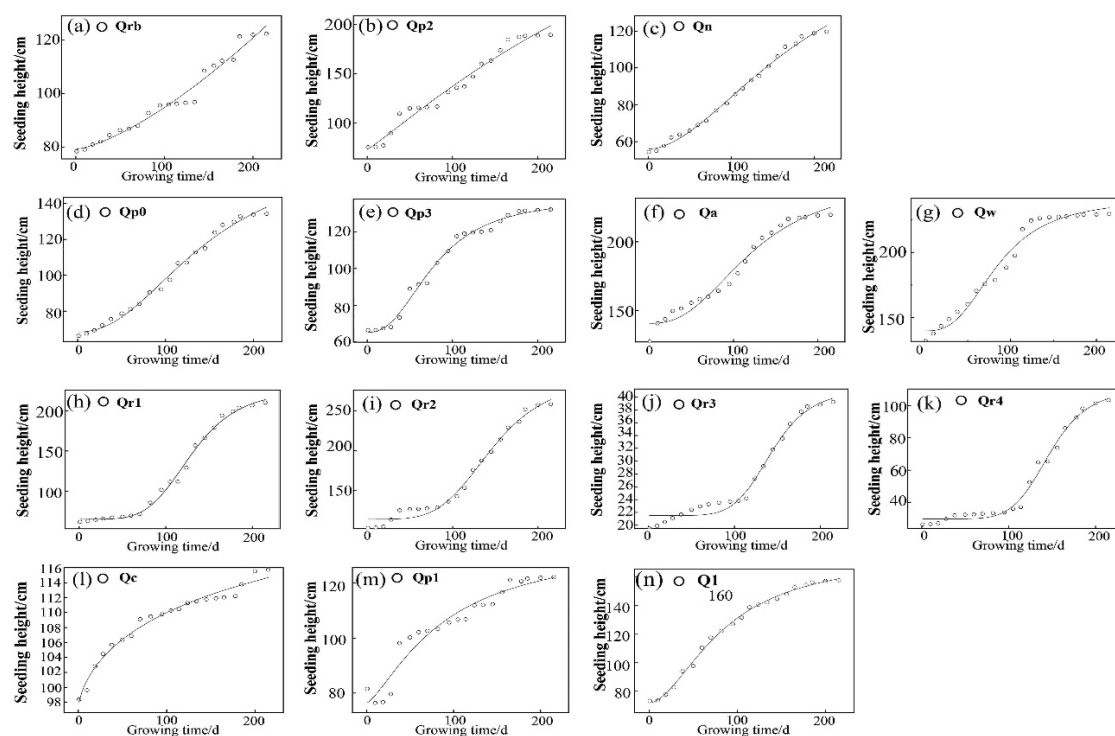


Figure S3. Fitted curve of dynamic growth related to oak seedling height. a-c; d-k; l-n: three mainly patterns of fitted curves for oak seedling height. All fitted curves were estimated based on the 200 days investigation.

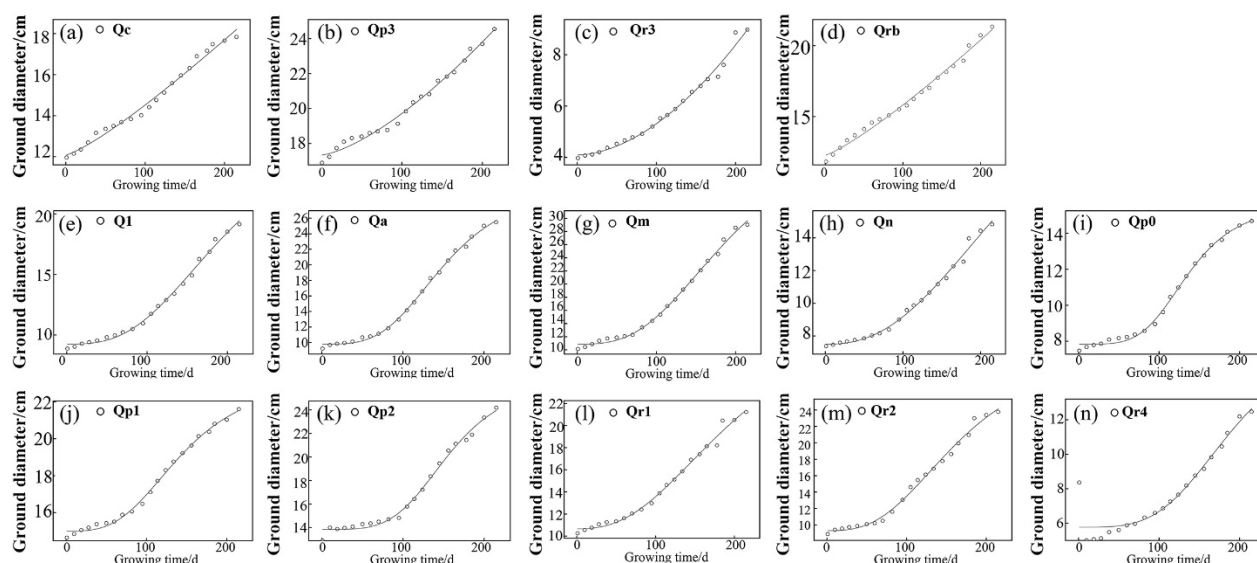


Figure S4. Fitted curve of dynamic growth related to oak ground diameter.a-d;e-n: two mainly patterns of fitted curves for oak ground diameter. All fitted curves were estimated based on the 200 days investigation.

Supplementary Tables

Table S1. Analysis of photosynthetic parameters for 11 oak candidates

Date	Oak varieties	E/mmol m ⁻²	Ci/ μ mol mol ⁻¹	Ca/ μ mol mol ⁻¹	gsw/mol m ⁻² s ⁻¹	gtw/mol m ⁻² s ⁻¹	chlorophyll content/ μ g m ⁻¹
19 th July	Q1	0.001±0.085a	483.633±20.954abc	396.028±0.953ab	0.000±0.002a	0.001±0.000a	80±3.39e
	Qa	0.141±0.088a	722.140±629.346abc	404.433±5.345ab	0.005±0.004b	0.004±0.004a	68±1.01c
	Qd	0.077±0.361a	1009.312±128.814a	397.631±1.691ab	0.002±0.000bc	0.002±0.000a	70±3.26bc
	Qm	0.003±0.005a	95.880±545.593c	401.315±0.121ab	0.000±0.001bc	0.000±0.000a	37±0.75a
	Qn	0.101±0.107a	363.452±238.635abc	406.371±5.286ab	0.002±0.000bc	0.002±0.003a	13±3.18g
	Qp3	0.011±0.008a	17.838±1305.844ab	395.854±0.658ab	0.011±0.005a	0.000±0.001a	63±0.45d
	Qr1	0.255±0.087a	864.759±302.123abc	411.403±2.289ab	0.001±0.001a	0.011±0.004a	0±1.53bc
	Qr4	0.031±0.035a	398.756±1.585a	223.577±2.290b	0.000±0.000ab	0.001±0.001a	10±0.82a
	Qrb	0.065±0.054a	220.277±144.985bc	394.547±2.200ab	0.002±0.001ab	0.000±0.000a	60±1.42c
	Qru2	0.098±0.066a	409.988±196.808abc	458.950±95.623ab	0.001±0.000ab	0.002±0.001a	00±0.87f
	Qw	0.035±0.001a	401.198±3.013abc	648.532±94.340a	0.002±0.003ab	0.001±0.000a	70±1.15b
31 th July	Q1	4.573±2.520bc	390.065±63.941bc	388.161±2.427a	0.134±0.089ab	0.128±0.083ab	70±1.14de
	Qa	5.909±0.298bc	224.665±11.420c	373.098±6.251a	0.172±0.021ab	0.162±0.018ab	17±1.00ab
	Qd	4.985±1.623bc	390.268±0.232bc	312.985±31.831ab	0.085±0.040b	0.082±0.037b	13±0.93bc
	Qm	5.206±0.217d	324.965±0.407d	347.656±11.970ab	0.125±0.001ab	0.119±0.001ab	83±2.32a
	Qn	6.434±1.190bc	393.591±3.366bc	322.563±26.914ab	0.131±0.066ab	0.125±0.061ab	87±2.06g
	Qp3	3.243±2.251bc	401.266±27.207bc	185.233±224.098b	0.086±0.033b	0.083±0.031b	50±2.46f
	Qr1	7.993±4.404c	352.958±51.504c	323.231±83.319ab	0.281±0.240a	0.255±0.211a	13±5.41ef
	Qr4	1.430±0.182e	183.552±104.876e	423.701±13.942a	0.020±0.011b	0.019±0.011b	43±0.21a
	Qrb	5.769±5.870bc	398.290±16.253bc	280.593±93.882ab	0.186±0.168ab	0.171±0.147ab	17±1.32cd
	Qru2	4.082±2.992a	528.237±157.429a	390.198±77.462a	0.082±0.044b	0.079±0.041b	47±0.25g
	Qw	1.268±0.178ab	528.237±157.430ab	431.316±1.032a	0.082±0.045b	0.026±0.005b	13±2.37ab
16 th August	Q1	4.554±0.658ab	399.082±20.952a	395.223±10.558ab	0.188±0.033ab	0.196±0.014ab	37±1.25g
	Qa	4.241±0.654ab	301.55±30.969a	455.703±5.909a	0.190±0.044ab	0.171±0.031ab	23±0.35d
	Qd	3.371±0.516ab	295.625±33.764a	402.883±1.267ab	0.123±0.023ab	0.119±0.022ab	83±1.95e
	Qm	4.134±0.619ab	289.447±3.278a	403.804±2.523ab	0.152±0.031ab	0.145±0.028ab	13±0.57bc
	Qn	5.248±2.818ab	332.672±14.695a	398.342±6.798ab	0.132±0.037ab	0.984±1.485ab	93±0.95h
	Qp3	3.090±1.501ab	282.514±128.122a	402.370±9.426ab	0.130±0.080ab	0.086±0.012ab	00±1.05i
	Qr1	6.840±1.503a	341.453±0.655a	482.037±8.223a	0.368±0.110a	0.333±0.092a	67±2.02a
	Qr4	2.184±4.582b	401.256±165.899a	418.591±6.206ab	0.134±0.207ab	0.079±0.010ab	67±1.59b
	Qrb	2.009±0.931b	289.377±69.402a	403.397±1.211ab	0.061±0.043ab	0.060±0.042ab	20±0.79f
	Qru2	4.336±0.886ab	314.785±51.400a	407.918±8.822ab	0.160±0.036ab	0.109±0.059ab	33±2.02i
	Qw	4.737±1.567ab	269.046±27.758a	426.486±16.358ab	0.183±0.074ab	0.120±0.191ab	70±0.50cd

Different low-case letters indicated significant differences among the 11 oak candidates, $p < 0.05$. E: the transpiration rate, Ci: intercellular CO₂ concentration, Ca: leaf chamber CO₂ concentration, gsw: stomatal conductance, gtw:total vapour conductance.

Table S2. Correlation analysis of growth and photosynthetic traits.

Species	Seedling height	Seedling diameter	Chlorophyll content	Leaf area	Leaf length	Leaf width	Leaf aspect ratio	Leaf form factor	Leaf gap	E	Ci	Ca	gsw	gtw
Seedling height	1.000													
Seedling diameter	0.727**	1.000												
Chlorophyll content	0.109	0.735**	1.000											
Leaf area	0.491	0.795**	0.445	1.000										
Leaf length	0.555	0.890**	0.482	0.936**	1.000									
Leaf width	0.400	0.292	0.036	0.682*	0.527	1.000								
Leaf aspect ratio	0.482	0.507	0.173	0.845**	0.718*	-0.891**	1.000							
Leaf form factor	0.000	0.219	0.355	-0.100	0.000	-0.718*	-0.527	1.000						
Leaf gap	-0.393	0.002	0.210	-0.489	-0.315	-0.881**	-0.785**	0.785**	1.000					
E	0.764**	0.155	-0.291	0.300	0.336	0.145	0.373	0.045	-0.315	1.000				
Ci	-0.255	-0.506	-0.560	-0.292	-0.287	0.036	-0.251	-0.232	0.009	-0.323	1.000			
Ca	-0.582	0.260	0.391	0.055	-0.009	-0.136	-0.064	0.136	0.311	-0.473	-0.282	1.000		
gsw	0.720*	0.227	-0.241	0.237	0.296	0.109	0.287	0.087	-0.110	0.834**	-0.178	-0.483	1.000	
gtw	0.709*	0.192	-0.273	0.218	0.273	0.118	0.300	0.045	-0.137	0.845**	-0.178	-0.491	0.998**	1.000

* and ** indicate significant and highly significant correlations at the levels of 5% and 1%, respectively. Red and green indicate positive and negative correlations, respectively.

Table S3. Principal component loading matrices and variance contributions of eight feature indices

Feature vector	Index	PC1	PC2
X1	Ground diameter	0.306	-0.333
X2	Seedling height	0.452	-0.175
X3	chlorophyll content	0.264	-0.070
X4	E	0.479	0.047
X5	Leaf length	0.181	0.620
X6	Leaf area	-0.011	0.651
X7	gsw	0.440	0.202
X8	gtw	0.420	-0.041