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Performance Evaluation of New Table Grape Varieties under High Light Intensity Conditions Based on the Photosynthetic and Chlorophyll Fluorescence Characteristics

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Abstract: The evaluation of photosynthetic characteristics of plants is important for the success rate of germplasm introduction. To select grape varieties with higher adaptability and trait performance, this experiment is aimed at evaluating and comparing the photosynthetic indices, chlorophyll fluorescence parameters, photosynthetic pigment content, and leaf characteristics of five Chinese hybrid varieties. The results showed that under high light intensity stress, the leaf growth of 'Ruidu Cuixia' was most affected and its specific leaf weight was the lowest, while 'Jing Hongbao' had the highest chlorophyll content. The maximum net photosynthetic rate (P_{nmax}), maximum light quantum yield (F_v/F_m), and apparent quantum efficiency (AQE) were different among varieties. It was reported that the 'Ruidu Zaohong' variety had the highest P_{nmax}. 'Ruidu Wuheyi' was found to have the highest F_v/F_m, while the highest AQE was recorded for 'Ruidu Cuixia', with intercellular CO_2 concentration (C_i) and stomatal conductance (gs) at 292.56 μmol·mol^{-1}, 766.56 mmol·m^{-2}·s^{-1}, and 66.8 μmol·m^{-2}·s^{-1}, respectively. The indices of ABS/CS_m, TR_o/CS_m, and DI_o/CS_m were significantly different among varieties, and these indices of 'Ruidu Zaohong' were the highest. P_n was positively correlated with C_i and T_r, gs were positively correlated with F_v and TR_o/CS_m. The specific leaf area was negatively correlated with F_v/F_m and Φ_{DIo}. The results of the principal component analysis and TOPSIS comprehensive evaluation showed that 'Jing Hongbao' and 'Ruidu Cuixia' performed best. Overall, the measurement of the photosynthetic characteristics of the plants during the growing period provided valuable data for the varietal introduction strategies. The better photosynthetic performance of 'Jing Hongbao' and 'Ruidu Cuixia' indicates more adaptability to the long day, high light intensity, and the high-temperature climate of Xinjiang.

Keywords: grapes; grape hybrid varieties; adaptation; photochromism; fluorescence

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1. Introduction

A natural climate of large temperature differences between day and night, long sunshine hours, and a dry climate [1] have always been advantageous for quality grape production. Traditional local varieties, owing to their geographical advantages, dominate most of the grape market and are the best-selling fruit products of the season in grape-growing areas. China is the largest producer of table and fresh grapes in the world (OIV 2022; https://www.oiv.int/what-we-do/country-report?oiv, accessed on 6 September

2023), and the Xinjiang region holds the top position in China. Grapes grown in Xinjiang are of good quality due to the unique climatic conditions in the region. However, the Xinjiang grape industry relies excessively on local varieties, resulting in a monotonous product structure that no longer meets the development needs of the grape industries.

To enrich the table grape variety resources in the region and enhance the efficiency and competitiveness of the Xinjiang grape industry, the Institute of Horticultural Crops at the Xinjiang Academy of Agricultural Sciences introduced several superior new grape varieties in 2019 for regional trial observation. The aim was to offer wider varieties for production. The current study hypothesized that the performance of newly introduced table grape varieties, when exposed to high light intensity conditions, will demonstrate significant differences in their photosynthetic and chlorophyll fluorescence characteristics, suggesting that certain varieties will exhibit superior adaptability and resilience to elevated light levels compared to others. The assessment of the success of introduced species depends significantly on the adaptive capacity of the introduced plants, including their ability to adapt to the local environment through seasonal rhythmic growth and development patterns, high production yield, and other relevant ecological and economic factors [2,3].

Photosynthesis is an important indicator of plant growth and production [4] and consists of components such as photosynthetic pigments, electron transport systems, and photosystems, each of which can potentially be affected by abiotic stresses [5]. Therefore, the study of photosynthesis performance in plants can reveal their growth potential [6], and it can be used as a basis for judging the success of plant variety introduction. Du et al. [7] showed that carbon metabolism was severely impaired under low nitrogen stress, leading to a decrease in the CO_2 assimilation rate, which accumulates in the cells and affects the overall photosynthetic rate. This phenomenon is mainly caused by stomatal and non-stomatal factors. In recent years, chlorophyll fluorescence detection techniques have been widely used to monitor the photosynthetic capacity of plants under different growth conditions, such as drought stress [8], salt stress [9], nitrogen stress [10], and high-temperature stress [11], etc. The results of Kromdijk et al. [12] showed that the q_P and NPQ of plants were always fluctuating under different stress conditions and became the standard to measure the inhibition of the electron transport chain. According to the results of Zhao et al. [13], the study of fluorescence kinetics is helpful in understanding the light-capturing ability of photosynthetic pigments and their tolerance to high-photon flux density in real-time, and to judge the photosynthetic capacity of plants under the current growth environment.

Fluorescence characteristics are extensively used in many studies related to plant physiology and photochemistry [14]. Chlorophyll fluorescence studies can also detect gross photosynthesis in large areas. In photosystem II (PSII), three pathways—chlorophyll fluorescence, photochemical reactions, and non-photochemical quenching (NPQ)—dissipate all of the light energy absorbed by the leaf. Some recent studies have demonstrated that stress conditions in plants can significantly influence photosynthetic physiology. Hazrati et al. [15] identified that both light intensity and water stress have a drastic impact on phytochemistry and fluorescence in *Aloe vera* plants. In a separate study, it was discovered that heat stress has a pronounced impact on the chlorophyll fluorescence properties of Rhododendron leaves [16]. Some studies including peony plants revealed that high-temperature stress directly influences chlorophyll fluorescence induction kinetics [17]. The direct impact of heat stress on plant fluorescence activity suggests its potential use as an indicator of heat stress [18]. Therefore, leaf photosynthesis measurements can be used as an indicator of plant adaptability to environmental changes and as a criterion for predicting plant domestication potential, and provide a scientific basis for enriching table grape variety resources in Xinjiang [19,20].

In this study, five Chinese own hybrid varieties, namely 'Ruidu Xiangyu', 'Ruidu Cuixia', 'Ruidu Zaohong', 'Ruidu Wuheyi', and 'Jing Hongbao', were used as indicators of plant adaptation. This study aimed to evaluate the physiological parameters of photosynthetic characteristics, chlorophyll fluorescence, chlorophyll content, and leaf appearance of these five new Chinese own hybrid varieties. The objective was to assess their adaptability to the climate in Xinjiang and provide a reference for the introduction of suitable newer grape varieties.

2. Materials and Methods

2.1. Experimental Site Overview

The study was carried out at the grape research base (87°28′ E, 45°56′ N) of the Urumqi Anningqu Experimental Field, Xinjiang Academy of Agricultural Sciences, Urumqi, China. The base is located on the northern slope of the Tianshan Mountains on the southern margin of the Junggar Basin. The average altitude is 600~800 m, and the terrain is gentle. The area is under the typical temperate range of arid and semi-arid continental climates. For this experimental field, the mean annual temperature was recorded at 7.13 °C, the accumulated temperature of ≥10 °C was 3000~3500 °C, and the annual sunshine hours were 2500~3000 h.

2.2. Experimental Plant Materials

Five Chinese hybrid grape varieties, 'Ruidu Xiangyu', 'Ruidu Cuixia', 'Ruidu Zaohong', 'Ruidu Wuheyi', and 'Jing Hongbao', were used as experimental materials (Table 1). The introduced varieties were planted in 2019. The plant rows were oriented north to south, with vine spacing of 1 by 3.5 m. The Y-shaped tree planting was adopted. The soil of the vineyard is sandy loam. Recommended vineyard practices, including canopy and disease management, were followed during the growing season. Normal soil fertilizer and drip system was installed for water management.

Table 1. Introduction of five new table grape varieties.

Varieties	Species	Parent	Breeding Units	Breeding Year
Ruidu Xiangyu	Eurasian	Jingxiu × Xiangfei	Institute of Forestry and Fruit Science, Beijing Academy of Agriculture and Forestry Science	In December 2007, it was approved by Beijing Forest Variety Examination and Approval Committee
Ruidu Cuixia	Eurasian	Jingxiu × Xiangfei	Institute of Forestry and Fruit Science, Beijing Academy of Agriculture and Forestry Science	In December 2007, it was approved by Beijing Forest Variety Examination and Approval Committee
Ruidu Zaohong	Eurasian	Jingxiu × Xiangfei	Institute of Forestry and Fruit Science, Beijing Academy of Agriculture and Forestry Science	In December 2014, it was approved by Beijing Forest Variety Examination and Approval Committee
Ruidu Wuheyi	Eurasian	Xiangfei × Hongbaoshi seedless	Institute of Forestry and Fruit Science, Beijing Academy of Agriculture and Forestry Science	In 2009, it was approved by the Beijing Forest Variety Examination and Approval Committee
Jinghongbao	Eurasian	Guibao × Wuhebai Jixin	Fruit research institute of Shanxi Academy of Agricultural Sciences	In 2012, it was approved by Shanxi Provincial Crop Variety Examination and Approval Committee

2.3. Test Equipment and Test Reagents

CIRAS-3 PP Systems photosynthetic analyzer (Amesbury, MA, USA; JUNIOR-PAM fluorometer (Heinz Walz GmbH, Effeltrich, Germany). Anhydrous ethanol procured from Tianjin Kaitong Chemical Reagent Co., LTD, Tianjin, China.

2.4. Test Methods

2.4.1. Photo-Response Curve Determination

P_n-PAR response curve related measurements were recorded at 10:30 and 12:30 (UTC +08.00, Beijing Time) on sunny days. Three disease-free plants with moderate vigor were selected from each variety. From the fourth to fifth nodes of the new shoots, three leaves were chosen. These leaves had good leaf color, similar size dimensions, and were free from diseases and insect pests [21]. The CIRAS-3 PP Systems photosynthetic analyzer (Amesbury, MA, USA) was used to measure the light response indices of the leaves [22,23]. A PLC3 universal leaf cuvette light source leaf chamber was utilized, and 10 gradients ranging from 0 to 2500 μmol·m^{-2}·s^{-1} (2500, 2000, 1500, 1000, 750, 500, 300, 150, 75, 0 μmol·m^{-2}·s^{-1}) were set by the light source. The data were automatically recorded, with each gradient being stable for 90 s. The net photosynthetic rate (P_n), stomatal conductance (gs), transpiration rate (T_r), intercellular CO_2 volume fraction (C_i), and water use efficiency (WUE) were measured using CIRAS-3 portable photosynthesis system (PP Systems, Amsbury, MA, USA). The readings were automatically recorded by CIRAS-3 after a certain interval. Few parameters like relative humidity (60%), CO_2 concentration (380 μmol mol^{-1}), and leaf temperature (28 °C) were maintained using an automatic control device on the instrument. Red-blue light (90%: 10%) was provided inbuilt LED light unit in the CIRAS-3. Photosynthesis-light response simulations were conducted using the leaf drift model [24], and the model fitting equation was employed.

$$P_n = \alpha \frac{1 - \beta I}{1 + \gamma I} I - R_d$$

Note: α is initial quantum efficiency; I symbolize photosynthetically active radiation (μmol·m^{-2}·s^{-1}); R_d is dark respiration rate (μmol·m^{-2}·s^{-1}); β is photoinhibition coefficient (m^2·s·μmol^{-1}); γ is light saturation coefficient (m^2·s·μmol^{-1}).

2.4.2. Measurement of Chlorophyll Fluorescence Parameters

The chlorophyll fluorescence parameters of varieties were measured with the same leaves that were used for photosynthetic index measurements. The JUNIOR-PAM fluorometer was used, with a 30-min dark acclimatization period before the measurements. Based on studies by Strasser et al. [25] and Tsimilli Michael [26], the following parameters were defined and calculated: actual light energy conversion efficiency (Φ_{PSII}), non-fluorescence quenching (Y_{NPQ}), photosynthetic electron transport rate (ETR), maximum light quantum yield (F_v/F_m), as well as other indicators. These parameters include the maximum yield of primary photochemical reactions (Φ_{Po}), heat dissipation per unit area (Φ_{Do}), light energy captured per unit reaction center (RC) (TR_o/CS_m), and heat dissipation per unit area (DI_o/CS_m).

2.4.3. Measurement of Leaf Appearance Traits

Twenty mature leaves were randomly selected from both, the sunny and shaded sides of the grape trellis for all three plants. These leaves were measured for photosynthetic indicators. The leaf area was measured using a leaf area meter, and the leaf weight was determined using digital electronic balance. The specific leaf weight (calculated as the single leaf weight divided by the leaf area) and specific leaf area (calculated as the leaf area divided by the single leaf weight) were calculated.

2.4.4. Measurement of Chlorophyll Content

The chlorophyll content of each of the three plants was measured using the photosynthetic index determination method. Five leaves with similar leaf color, size, and exposure to sunlight were selected. The leaves were ground into a powder, with a weight of 0.2 g selected for analysis. They were then mixed with 80% acetone and kept in darkness for 12 h until the sample turned white. Afterward, the mixture was filtered, and absorbance values were measured at wavelengths of 645 nm, 663 nm, and 470 nm. These values were recorded, and the contents of Chl a (chlorophyll a), Chl b (chlorophyll b), and carotenoids were determined, following Arnon's method [27].

2.4.5. TOPSIS Evaluation Method

The TOPSIS integrated evaluation method was used to synthesize the chlorophyll content, chlorophyll fluorescence parameters, and photosynthetic characteristic parameters of the leaves of the five varieties to comprehensively evaluate the photosynthetic strength of the five varieties.

In step 1, the indicators were homogenized to avoid affecting the description of the results.

Step 2, normalization of the data.

$$Y_{ij} = \frac{X}{\sqrt{\sum_{j=1}^{m} X_j^2}},\ (j = 1, 2, \ldots m)$$

In the formula, j represents a certain evaluation indicator, and m represents the number of evaluation indicators.

Step 3: Calculate the distance between positive and negative ideal solutions (D±) and the relative closeness degree (C):

$$D^+ = \sqrt{\sum_{j=1}^{m} W_j \left(A_j^+ - Y_{ij}\right)^2},\ (j = 1, 2, \ldots m)$$

$$D^- = \sqrt{\sum_{j=1}^{m} W_j \left(A_j^- - Y_{ij}\right)^2},\ (j = 1, 2, \ldots m)$$

In the formula, j represents an evaluation index, m represents the number of evaluation indexes, W_j represents the weight value of the jth index, A_j^+ represents the optimal scheme data of the jth index, A_j^- represents the worst scheme data of the jth index and Y^{ij} represents the corresponding data of a certain evaluation object i for the jth indicator.

$$C_j = \frac{D^-}{D^- + D^+}$$

In the formula, the value of C_j ranges from 0 to 1. The larger C_j is, the stronger the photosynthetic capacity of the jth new variety is, and the closer the variety's adaptability to the climate in Xinjiang is to the optimal level.

2.5. Data Processing and Statistical Analysis

All the data were collated in at least three replications and tabulated using Microsoft Excel 2010, and the results were statistically analyzed by analysis of variances tests (one-way ANOVA). We used SPSS 25.0 (SPSS Inc., Chicago, IL, USA) to perform Pearson correlation analysis and principal component analysis, and photo-response curves were fitted and plotted using Origin 2019.

3. Results

3.1. Chlorophyll Content and Leaf Appearance Traits

There were significant differences in leaf characteristics among the five new table grape varieties ($p < 0.05$) (Figure 1). The results showed that the leaf area and single-leaf weight of 'Ruidu Zaohong' were the highest among the five varieties (Figure 1A,B). The specific leaf area of 'Ruidu Cuixia' was 8.99% higher than that of 'Ruidu Zaohong' (Figure 1D). As shown in Figure 1C, there was no significant difference in specific leaf weight among the five new table grape varieties.

The chlorophyll content of higher plants affects the metabolic rate of the plant and is an index for judging plant health and local adaptation. The results showed that the chlorophyll content of the five new varieties differed significantly ($p < 0.05$) (Figure 2). 'Jing Hongbao' had the highest chlorophyll a, chlorophyll b, and total chlorophyll content, which were 29.36%, 139.02%, and 59.33% higher than those of 'Ruidu Zaohong', respectively.

Interestingly, 'Jing Hongbao' had the lowest values of carotenoid content and chlorophyll a/b, 32.08% lower than 'Ruidu Cuixia' and 46.47% lower than 'Ruidu Zaohong'.

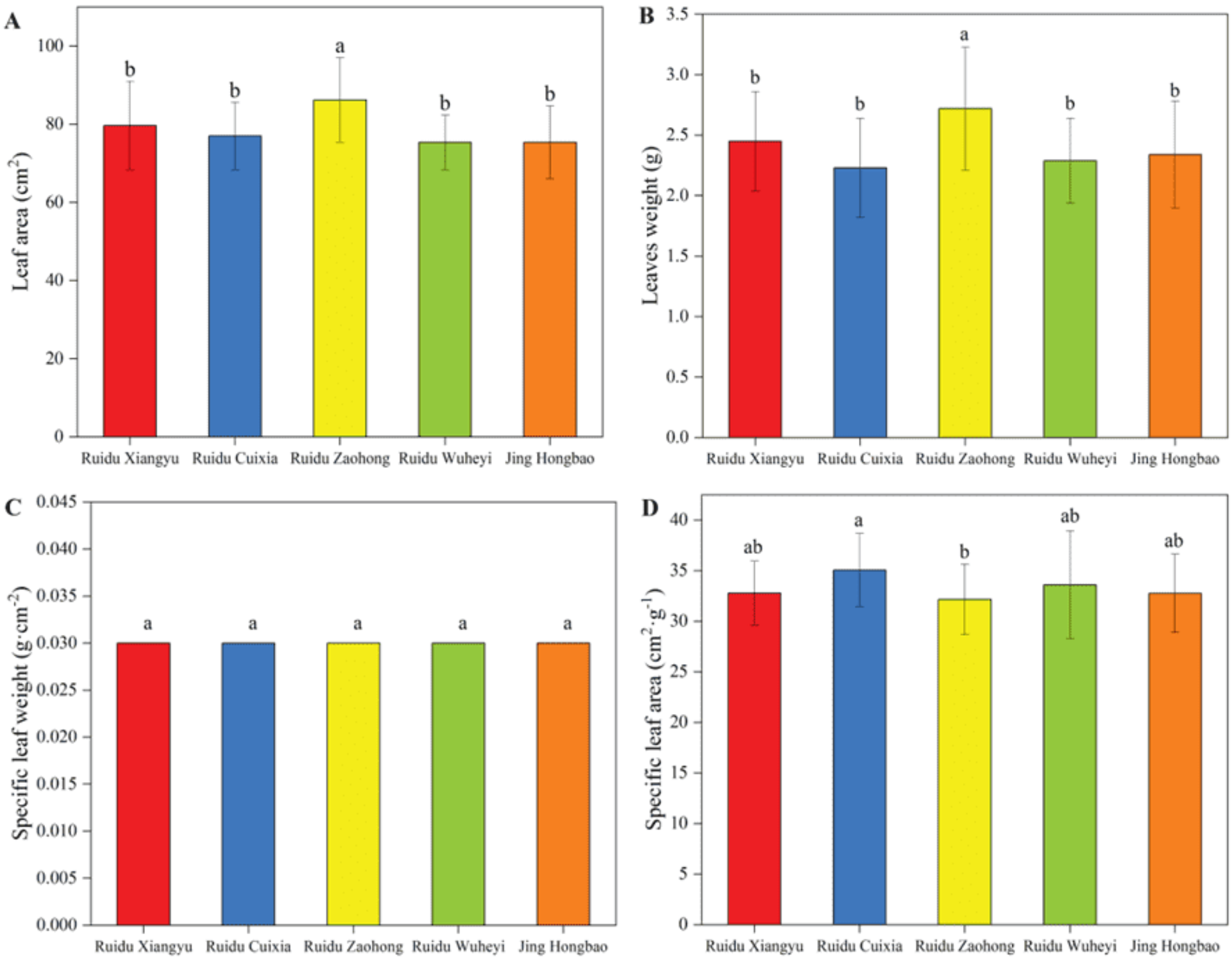

Figure 1. Comparison of leaf characteristic parameters of five new table grape varieties. Same letter in the same figure indicates that there is no significant difference. The data in the figure are mean ± standard deviation, and different lowercase letters indicate significant differences (p < 0.05). (**A**) Leaf area; (**B**) Leaf weight; (**C**) specific leaf weight; (**D**) specific leaf area.

3.2. *Photosynthetic Parameters and Photo-Response Curve*

Photosynthetic parameters for all the varieties were measured. From Figure 3, it can be determined that all five photosynthetic parameters of 'Ruidu Xiangyu' were lower than those of the other four varieties, with an average C_i of 194.67 μmol·mol^{-1}, which is 33.46% lower than that of 'Ruidu Cuixia' (Figure 3A). The gs is 145.56 mmol·m^{-2}·s^{-1}, which is 81.07% lower than that of 'Ruidu Cuixia' (Figure 3B). The P_n is 9.64 μmol·m^{-2}·s^{-1}, which is 52.14% lower than that of 'Ruidu Zaohong' (Figure 3C). The T_r is 5.88 mmol·mol^{-1}, which is 49.18% lower than that of 'Jing Hongbao' (Figure 3D).

Finally, the average WUE is 1.64 mmol·m^{-2}·s^{-1}, which is 15.46% lower than that of 'Ruidu Zaohong' (Figure 3E).

Fitting curves of the light response of five new table grape varieties were also observed. The fitting curve presented in Figure 4 showed that the light response curve of all five varieties shows a similar trend. With the increase in photosynthesis active radiation, the net photosynthesis rate gradually increases. After reaching the saturation light intensity, it stabilizes or slightly decreases. There are significant differences in the net photosynthesis rate of the five varieties under high light intensity.

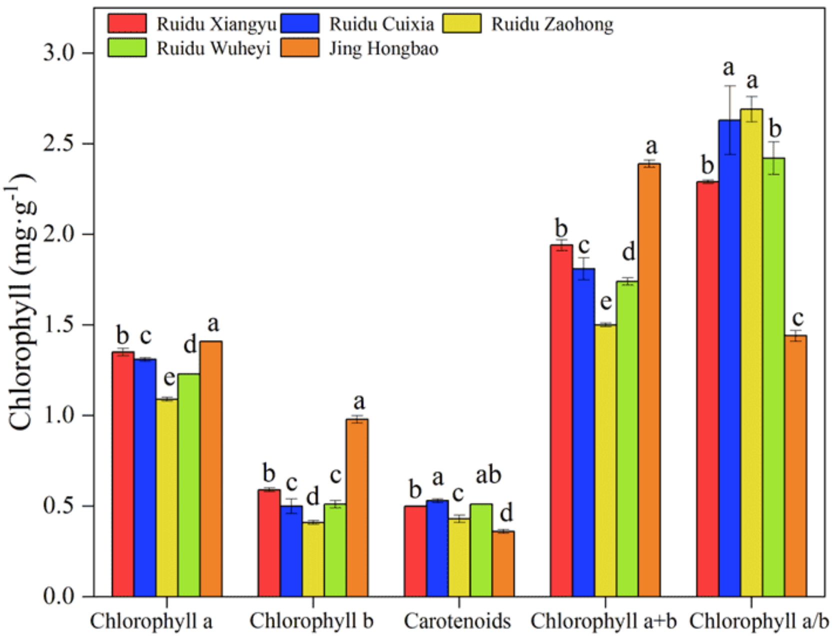

Figure 2. Comparison of chlorophyll content in varieties. The error bar indicates the standard deviation obtained from three biological replicates. Same letter in the same figure indicates that there is no significant difference. The data in the figure are mean ± standard deviation, and different lowercase letters indicate significant differences ($p < 0.05$).

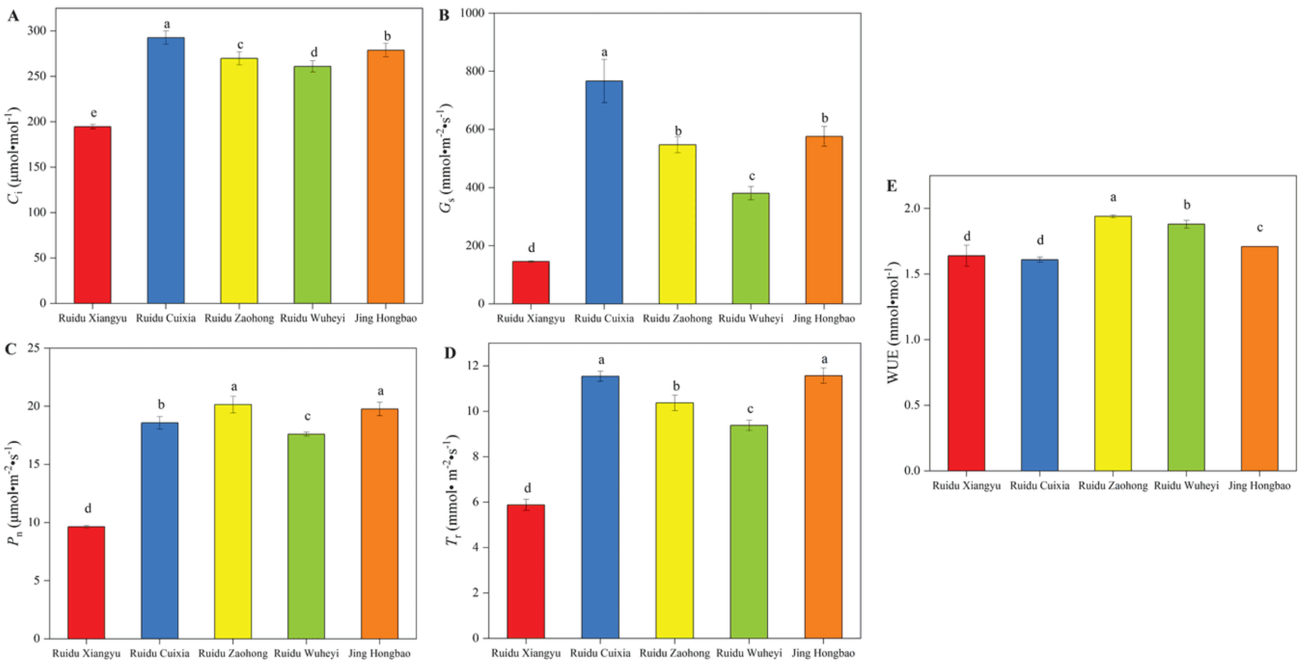

Figure 3. Comparison of photosynthetic parameters of five new table grape varieties. C_i (**A**), gs (**B**), P_n (**C**), T_r (**D**), and WUE (**E**) in the figure showed the difference in photosynthetic parameters of the five new varieties. Same letter in the same figure indicates that there is no significant difference. The data in the figure are mean ± standard deviation, and different lowercase letters indicate significant difference ($p < 0.05$).

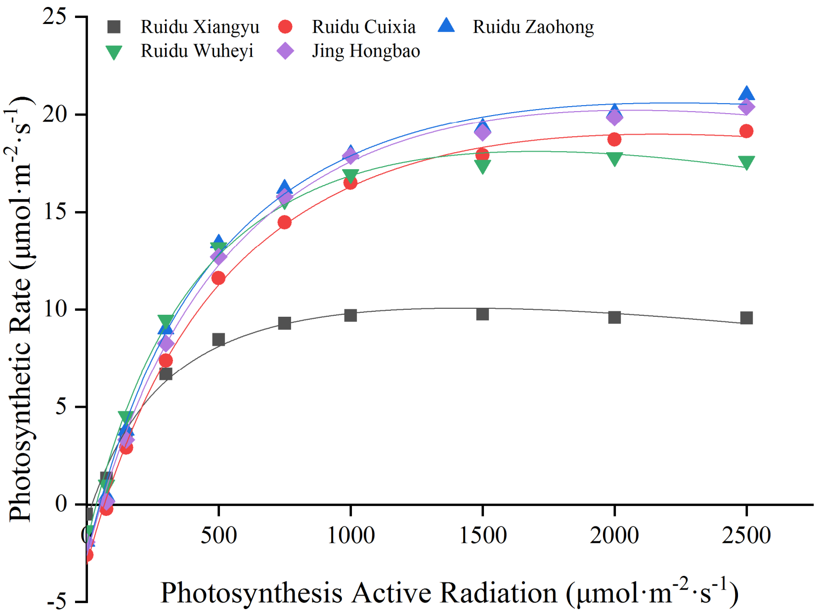

Figure 4. Fitting curves of light response of five new table grape varieties.

Based on the measured parameters of the P_n-PAR light response curve (Table 2), it can be observed that the photosynthetic characteristics of 'Ruidu Xiangyu' are the lowest among the five varieties. The mean value of its apparent quantum efficiency is 0.0298, which is 14.83% lower than that of 'Ruidu Wuheyi'. Its dark respiration rate is 0.85 μmol·m^{-2}·s^{-1}, which is 72.84% lower than that of 'Ruidu Cuixia'. Its light saturation intensity is 1437.1 μmol·m^{-2}·s^{-1}, which is 39.55% lower than that of 'Ruidu Zaohong'. Its light compensation point is 20 μmol·m^{-2}·s^{-1}, which is 70.06% lower than that of 'Ruidu Cuixia'. Finally, its maximum net photosynthesis rate is 9.8 μmol·m^{-2}·s^{-1}, which is 51.96% lower than that of 'Jing Hongbao'.

Table 2. Comparison of characteristic parameters of response curves of five new table grape varieties P_n-*PAR*.

Varieties	Right Angle Hyperbolic Modified Model	Apparent Quantum Efficiency	Adjust R-Square	Dark Respiration Rate/(μmol·m^{-2}·s^{-1})	Light Saturation Point/(μmol·m^{-2}·s^{-1})	Light Compensation Point/(μmol·m^{-2}·s^{-1})	Maximum Net Photosynthetic Rate/(μmol·m^{-2}·s^{-1})
Ruidu Xiangyu	$y = 0.04488x\frac{1-0.00012x}{1+0.00273x} - 0.85047$	0.0298	0.991	0.85	1437.1	20	9.8
Ruidu Cuixia	$y = 0.05172x\frac{1-0.00008x}{1+0.00147x} - 3.12694$	0.0371	0.998	3.13	2290.5	66.8	19.2
Ruidu Zaohong	$y = 0.05921x\frac{1-0.00007x}{1+0.00170x} - 2.69752$	0.0384	0.995	2.70	2377.4	49.6	21.0
Ruidu Wuheyi	$y = 0.05966x\frac{1-0.00011x}{1+0.00182x} - 2.02594$	0.0391	0.995	2.03	1734.3	36.4	17.8
Jing Hongbao	$y = 0.05297x\frac{1-0.00009x}{1+0.00139x} - 2.70940$	0.0356	0.996	2.71	2171.3	55.4	20.4

3.3. Chlorophyll Fluorescence Parameters

The dynamic parameters of chlorophyll fluorescence were mathematically analyzed for these five different grape varieties, aiming to characterize the structural and electron transfer performance of their photosynthetic apparatus. The analysis results reflect the photosynthetic performance of these grape varieties. Representative chlorophyll fluorescence parameters were summarized, revealing significant differences in the regulation ability of chlorophyll fluorescence in response to light intensity among the different varieties (Figure 5).

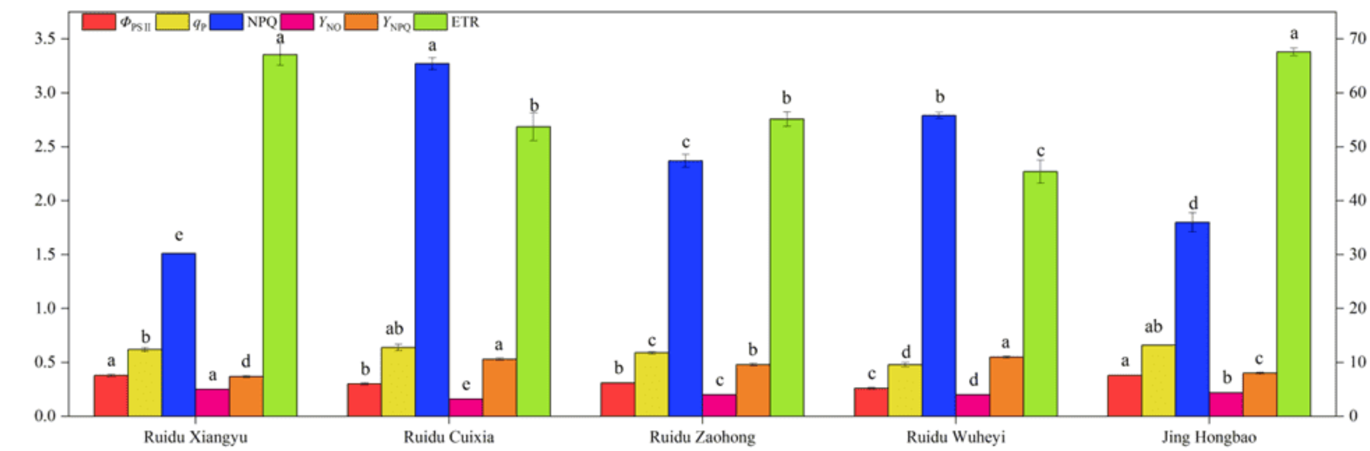

Figure 5. Significant differences in chlorophyll fluorescence parameters among five new table grape varieties. ETR in the figure is the right coordinate axis degree, and other indicators are the left coordinate axis degree. Same letter in the same figure indicates that there is no significant difference. The data in the figure are mean ± standard deviation, and different lowercase letters indicate significant difference ($p < 0.05$).

Analysis of chlorophyll fluorescence parameters revealed that the highest and lowest values of Φ_{PSII}, ETR, and q_P were observed in 'Jing Hongbao' and 'Ruidu Wuheyi', respectively (Figure 5). The mean values of Φ_{PSII}, ETR, and q_P for 'Jing Hongbao' were 0.38, 67.6, and 0.66, respectively, representing higher of 46.15%, 49.00%, and 37.50% compared to 'Ruidu Wuheyi'. Conversely, 'Ruidu Wuheyi' exhibited the highest mean value of Y_{NPQ} (0.55), while 'Ruidu Xiangyu' had the lowest mean value (0.37). In Figure 6, 'Ruidu Wuheyi' displayed the highest values of F_v/F_m and Φ_{Po}, while 'Ruidu Zaohong' had the lowest values. Additionally, 'Ruidu Zaohong' demonstrated superior performance in parameters such as Φ_{Do} and ABS/CS_m. The lowest values of ABS/CS_m and DI_o/CS_m were observed in 'Ruidu Wuheyi', whereas 'Ruidu Xiangyu' had the lowest value of TR_o/CS_m.

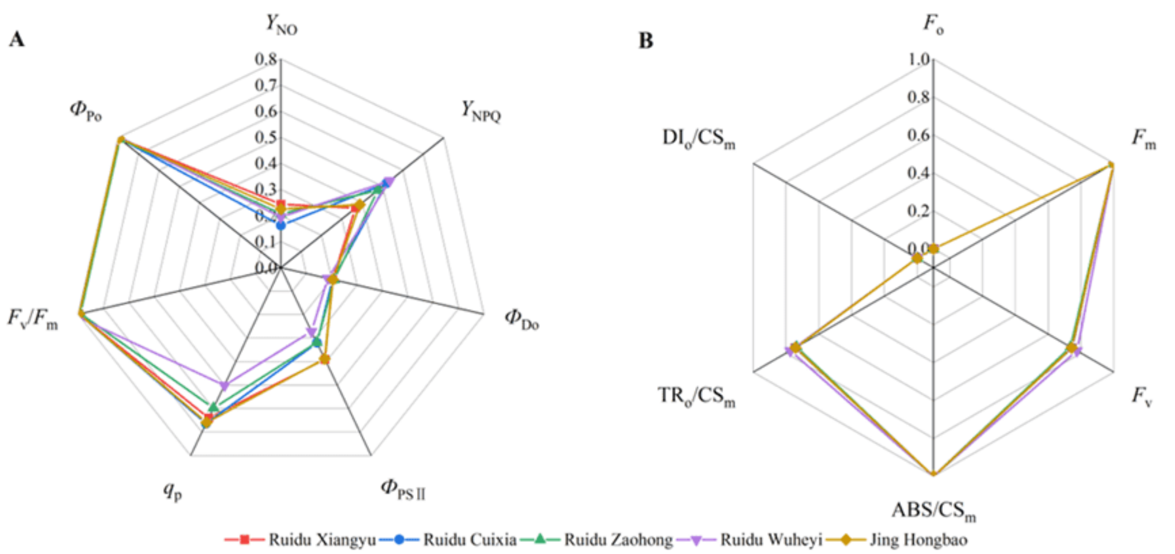

Figure 6. Comparison of fluorescence characteristic parameters of five new table grape varieties. (**A**) Φ_{Do}, Y_{NO}, Y_{NPQ}, Φ_{PO}, q_p, F_v/F_m, and Φ_{PSII}; (**B**) ABS/CS_m, DI_o/CS_m, TR_o/CS_m, F_v, and F_m.

3.4. Correlation Analysis and Hierarchical Cluster Analysis

The light adaptation ability of the five varieties was analyzed by hierarchical cluster analysis, and the results are presented in Figure 7A. From Figure 7A, it can be observed that the five varieties were divided into two categories based on clades, and their prominent characteristics. The first category includes 'Jing Hongbao', 'Ruidu Cuixia', and 'Ruidu Zaohong', which have the highest chlorophyll content and chlorophyll fluorescence parameters and lower light saturation intensity.

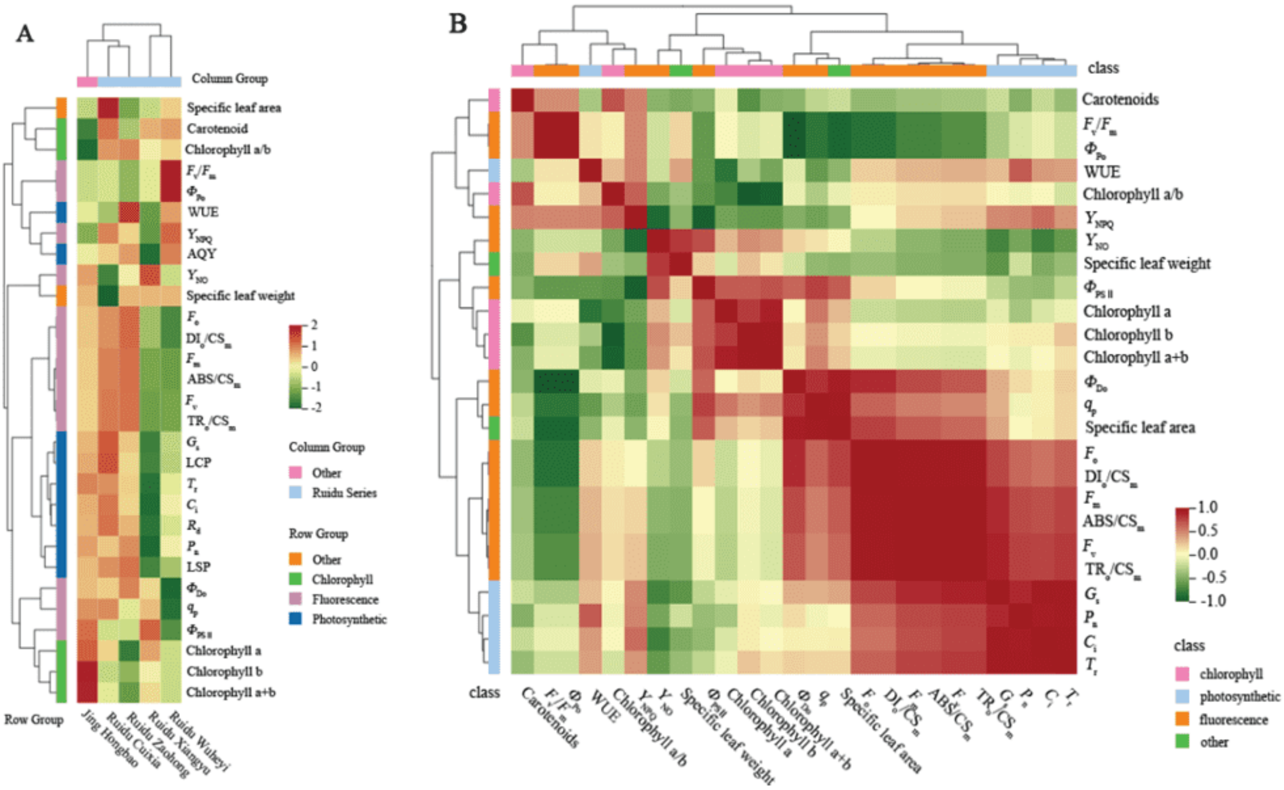

Figure 7. Correlation and hierarchical clustering analysis of chlorophyll content, chlorophyll fluorescence, and photosynthetic characteristic parameters of five new table grape varieties. (**A**) represents hierarchical cluster analysis, and (**B**) represents correlation analysis. Different colors of red and green in Panel B indicate a significant correlation at the 0.05 level (two-tailed). Red indicates a high positive correlation, green indicates a high negative correlation, the redder the color, the higher the positive correlation between different indicators, the greener the color, and the negative phase between different indicators.

The second category includes 'Ruidu Xiangyu' and 'Ruidu Wuheyi', which have lower chlorophyll content and chlorophyll fluorescence parameter values but higher apparent quantum efficiency values.

Pearson correlation analysis was performed on the 25 photosynthetic phenotypic indices of the five varieties (Figure 7B). From Figure 7B, it can be observed that P_n is significantly positively correlated with C_i and T_r ($p < 0.05$), and their correlation coefficients are all greater than 0.92. gs is significantly positively correlated with F_v and TR_o/CS_m, and its correlation coefficient is 0.885. Specific leaf area is significantly positively correlated with Φ_{Do} and q_P, and negatively correlated with Φ_{Po} and F_v/F_m ($p < 0.05$). Their correlation coefficients are all greater than 0.92.

Further correlation analysis results clearly showed that there is a good correlation between photosynthetic characteristics and chlorophyll fluorescence parameters, indicating that the evaluation of plant photosynthetic capacity needs to comprehensively consider both photosynthetic and chlorophyll fluorescence indicators.

3.5. Principal Component Analysis

Principal component analysis was performed on the 25 photosynthetic and chlorophyll fluorescence indicators in the experiment. Four principal components with eigenvalues greater than 1 were extracted (Table 3), accounting for a cumulative contribution rate of 100% and effectively retaining most of the information from the original variables. These four principal components were used for a comprehensive analysis of the photochemical efficacy of the five varieties. The eigenvectors of the principal components were calculated based on the principal component loading matrix and eigenvalues.

Table 3. Principal component characteristic values, contribution rate, and cumulative contribution rate of five new table grape varieties.

Principal Component Number	Eigenvalue	Rate of Contribution/%	Accumulating Contribution Rate/%
1	10.9385	43.75%	43.75%
2	7.3320	29.33%	73.08%
3	3.5369	14.15%	87.23%
4	3.1926	12.77%	100.00%

By multiplying the obtained eigenvectors with the standardized data and considering the proportion of eigenvalues corresponding to the four principal components relative to the total sum of eigenvalues, weights were determined. These weights were then utilized to calculate the composite scores of the principal components.

The results (Table 4) revealed the relative photosynthetic abilities of the five varieties as follows: 'Jing Hongbao' > 'Ruidu Cuixia' > 'Ruidu Zaohong' > 'Ruidu Xiangyu' > 'Ruidu Wuheyi'. To allow for comparison of the indicator scores, the scores of the four principal components were multiplied and summed with the squared variances' percentages of the extracted loadings. These values were subsequently divided by the cumulative percentages. The results (Table 5) showcased the varying weightings of the 25 indicators in leaf photosynthesis, with chlorophyll b, T_r, chlorophyll a + b, q_P, and gs ranking among the top 5.

Table 4. Comprehensive principal component scores of five new table grape varieties.

Varieties	F1	F2	F3	F4	F	Rank
Ruidu Xiangyu	−3.6070	2.3626	−0.6990	−1.8853	−1.2248	4
Ruidu Cuixia	2.9872	−1.5209	1.9314	−1.8010	0.9041	2
Ruidu Zaohong	2.8615	−0.7777	−2.8697	0.3004	0.6561	3
Ruidu Wuheyi	−3.4800	−3.2592	0.4389	1.3790	−2.2403	5
Jinghongbao	1.2383	3.1953	1.1984	2.0069	1.9048	1

Table 5. Scores of photosynthetic indexes of five new table grape varieties.

Indexes	F1	F2	F3	F4	F	Rank
Chlorophyll a	−0.0683	0.2336	0.3939	−0.0271	0.0673	16
Chlorophyll b	−0.0022	0.2730	0.2428	0.2771	0.1105	1
Carotenoids	−0.1108	−0.2200	0.1283	−0.3760	−0.1063	25
Chlorophyll a + b	−0.0272	0.2729	0.3128	0.1776	0.1003	3
Chlorophyll a/b	0.0285	−0.2691	−0.1971	−0.3176	−0.1002	24
C_i	0.2296	−0.1361	0.2000	0.2138	0.0863	12
gs	0.2706	−0.0866	0.1834	0.0891	0.0968	5
P_n	0.2299	−0.1105	0.0299	0.3205	0.0843	13
T_r	0.2424	−0.0692	0.1815	0.2534	0.1069	2
WUE	0.0835	−0.1826	−0.3069	0.3293	−0.0134	19

Table 5. *Cont.*

Indexes	F1	F2	F3	F4	F	Rank
F_v/F_m	−0.2076	−0.2165	0.1546	0.1772	−0.0816	22
Φ_{Po}	−0.2076	−0.2165	0.1546	0.1772	−0.0816	23
Φ_{Do}	0.2076	0.2165	−0.1546	−0.1772	0.0816	14
Φ_{PSII}	−0.0033	0.3635	0.0179	−0.0962	0.0708	15
q_P	0.1554	0.2587	0.1377	−0.2358	0.0988	4
Y_{NO}	−0.1478	0.2805	−0.2165	0.0768	−0.0023	18
Y_{NPQ}	0.0621	−0.3569	0.0759	0.0332	−0.0465	21
F_o	0.2910	0.0678	−0.0871	−0.0637	0.0942	6
F_m	0.3011	0.0068	−0.0422	−0.0205	0.0930	8
F_v	0.3017	−0.0156	−0.0254	−0.0046	0.0916	10
ABS/CS_m	0.3011	0.0068	−0.0422	−0.0205	0.0930	9
Tr_o/CS_m	0.3017	−0.0156	−0.0254	−0.0046	0.0916	11
DI_o/CS_m	0.2910	0.0678	−0.0871	−0.0637	0.0942	7
Specific leaf area	0.0419	−0.1743	0.4141	−0.2195	−0.0019	17
Specific leaf weight	−0.1528	0.1154	−0.3097	0.3106	−0.0273	20

3.6. Comprehensive Evaluation of Photosynthetic Capacity

The results (Tables 6 and 7) show that the photosynthetic capacity of the five new varieties of table grapes from strongest to weakest are: 'Jing Hongbao' > 'Ruidu Cuixia' > 'Ruidu Zhaohong' > 'Ruidu Wuheyi' > 'Ruidu Xiangyu'.

Table 6. Positive and negative ideal solutions of photosynthetic indexes of five new table grape varieties.

Indexes	Positive Ideal Solution A^+	Negative Ideal Solution A^-	Indexes	Positive Ideal Solution A^+	Negative Ideal Solution A^-
Chlorophyll a	0.492	0.38	Φ_{Po}	0.457	0.443
Chlorophyll b	0.695	0.291	Φ_{Do}	0.465	0.409
Carotenoids	0.506	0.344	Φ_{PSII}	0.513	0.356
Chlorophyll a + b	0.563	0.353	q_P	0.482	0.364
Chlorophyll a/b	0.513	0.276	Y_{NO}	0.523	0.349
C_i	0.499	0.341	Y_{NPQ}	0.518	0.355
gs	0.63	0.135	F_o	0.508	0.357
P_n	0.521	0.237	F_m	0.492	0.391
T_r	0.521	0.269	F_v	0.487	0.397
WUE	0.503	0.397	ABS/CS_m	0.492	0.391
Specific leaf area	0.462	0.424	Tr_o/CS_m	0.487	0.397
Specific leaf weight	0.453	0.424	DI_o/CS_m	0.508	0.357
F_v/F_m	0.457	0.443			

Table 7. TOPSIS evaluation and calculation results of five newly introduced table grape varieties.

Varieties	Positive Ideal Solution Distance D^+	Negative Ideal Solution Distance D^-	Degree of Relative Proximity C	Sorting Result
Ruidu Xiangyu	0.779	0.389	0.333	5
Ruidu Cuixia	0.434	0.769	0.639	2
Ruidu Zaohong	0.53	0.663	0.556	3
Ruidu Wuheyi	0.624	0.464	0.426	4
Jing Hongbao	0.367	0.78	0.68	1

4. Discussion

Photosynthetic pigments are an important part of the photosynthesis mechanism. Under the long-term strong light irradiation in Xinjiang during the daytime, the leaf pigment contents of the five varieties were quite different. The chlorophyll a and chlorophyll b contents of 'Ruidu Zaohong' were significantly lower than those of the other four varieties. The chlorophyll a + b content of 'Jing Hongbao' reached 2.39 mg·g^{-1}, with chlorophyll a at

1.41 mg·g^{-1} and chlorophyll b at 0.98 mg·g^{-1}, respectively. Its growth potential was better than that of the 'Ruidu' series.

The results of this experiment were consistent with Yan's findings in 2021. High temperature and strong light stress reduced the pigment content of the leaves, damaged the chloroplast structure in them, and inhibited photosynthesis. However, the chlorophyll a and b contents of 'Jing Hongbao' were higher, indicating that the plants can initiate self-protection mechanisms to meet their own growth needs under stress conditions [28].

Photosynthesis serves as an important indicator for testing the sensitivity of plants to environmental stress [29]. In the high temperature and high light intensity conditions of Xinjiang, the average P_n of 'Ruidu Zaohong' was as high as 20.14 μmol·m^{-2}·s^{-1}, whereas 'Ruidu Xiangyu' only reached 9.64 μmol·m^{-2}·s^{-1}. Moreover, 'Ruidu Cuixia' exhibited mean gs and C_i values that were 50.29% and 426.63% higher than those of 'Ruidu Xiangyu', respectively.

These findings suggest that higher temperatures and stronger light may lead to stomatal closure in 'Ruidu Xiangyu' leaves, thereby impacting the gas exchange rate. Consequently, this closure causes a decrease in gs and C_i, inhibiting photosynthetic efficiency by reducing photosynthetic assimilation substances and water loss, which aligns with the observations made by Tang et al. [30].

Plants possess a light radiation signal regulation system [31] that modulates both stomatal and non-stomatal factors based on the effective light radiation intensity. This regulation system influences various photosynthetic parameters in leaves. Research findings indicate that leaf damage due to excessive light results in reduced chlorophyll content, T_r value, and P_n value, ultimately diminishing photosynthetic capacity. This outcome is similar to the findings reported by Negi et al. [32]. Additionally, correlation analysis demonstrates a significant positive relationship between P_n, C_i, and T_r. Consequently, it is speculated that stomatal factors play a pivotal role in a plant's growth potential. Different grape varieties employ diverse mechanisms to coordinate their photosynthesis, utilizing CO_2 absorption, water uptake, and inorganic ion transport to adapt to their specific growth environments.

Chlorophyll fluorescence is a commonly used, non-destructive method for detecting plant physiological characteristics and stress traits, which further helps in increasing our understanding of the behavior of plants in their natural environments [33]. Previous research results have shown that the instantaneous fluorescence signal of PSII is primarily caused by the oxidation-reduction reaction of plastoquinone A (QA) [34]. QA represents the reduction state of the photosynthetic electron transport chain and is manifested as photochemical energy conversion and thermal dissipation [35,36]. F_v/F_m can estimate the maximum quantum yield of QA reduction, representing the potential efficiency of plant PSII [37].

Under non-stress conditions, the normal range of F_v/F_m for plant leaves is between 0.80 and 0.85. When under environmental stress, the F_v/F_m value will significantly decrease. The results of this study show that only 'Ruidu Wuheyi' F_v/F_m is greater than 0.81, indicating that the light duration and intensity in Xinjiang are suitable for the growth needs of this variety. The F_v/F_m of the other 4 varieties was slightly lower than 0.80, indicating that the plants were under environmental stress, which is speculated to be related to the reversible inactivation or downregulation of PSII caused by high light and heat [38]. F_v is related to the photo-acclimation state of the dark-adapted reaction center [39]. Q_P represents the proportion of the PSII reaction center capturing the excitation energy, TR_o/CS_m represents the light energy captured per unit area, Φ_{Po} represents the maximum quantum yield of the primary photochemical reaction, and Φ_{Do} represents the quantum yield of energy dissipation.

In this study, 'Ruidu Zhaohong' had the highest TR_o/CS_m and Φ_{Do} values, indicating that QA was affected by high light and heat stress and could not effectively transmit electrons to the next level Quinone receptor [40], resulting in severe energy loss.

In addition, the correlation analysis shows that gs is significantly positively correlated with F_v and TR_o/CS_m; specific leaf area is significantly positively correlated with Φ_{Do}

and q_P, and significantly negatively correlated with Φ_{Po} and F_v/F_m, which is inconsistent with the results of previous studies [9,41]. The reasons may be due to differences in the experimental plant varieties, changes in the growth environment, and uncertainties in the correlations between various photosynthetic parameters, and further research is needed to determine the specific reasons.

Photosynthesis in plants is controlled by several factors, such as environmental factors, growth and developmental stages, and nutritional status, which can lead to differences in response to plant traits. In this study, five Chinese own hybrid varieties grapes were selected and cultivated under normal water and fertilizer management. Their photosynthetic capacity was evaluated in relation to their phenotypic, physiological, and biochemical indicators. The varieties were ranked according to the combined scores of principal component analysis and TOPSIS.

The results showed that 'Jing Hongbao', 'Ruidu Cuixia', and 'Ruidu Zaohong' ranked in the top three positions in both evaluation methods. However, further research is needed to determine the photosynthetic capacity between 'Ruidu Xiangyu' and 'Ruidu Wuheyi', as they ranked in the bottom two positions.

Moreover, since grapes are a berry plant, the adaptability of grapes to the regional environment of Xinjiang still needs to be evaluated in terms of fruit quality and internal tissue structure, among other factors.

This study only analyzed the photosynthetic characteristics of the leaves, and further research will be conducted on the physiological characteristics of the fruits.

5. Conclusions

There were some differences in leaf photosynthetic performance, photosynthetic pigment content, and chlorophyll fluorescence parameters between the five hybrid varieties under cultivation conditions in Xinjiang. Overall, 'Jing Hongbao' and 'Ruidu Cuixia' exhibited a stronger ability to accumulate organic matter content through photosynthesis, and their utilization efficiency in a strong light environment was significantly higher than that of 'Ruidu Zaohong', 'Ruidu Xiangyu', and 'Ruidu Wuheyi', which demonstrated a strong resistance to strong light intensity stress. Based on the comprehensive evaluation results of photosynthetic traits for each variety using principal component analysis and TOPSIS analysis, it can be preliminarily concluded that 'Jing Hongbao' and 'Ruidu Cuixia' displayed stronger adaptability to the climate in Xinjiang and are suitable for cultivation in the region.

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