Effects of GA_3, CPPU and TDZ on Fruit Seedlessness and Quality of 'Xiangfei' Grape

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Abstract [**Objectives**] This study was conducted to investigate the application time, concentrations, and combinations of plant growth regulators, aiming to screen suitable concentrations, combinations, and treatment periods for enhancing the commercial quality of the fruit. [**Methods**] 'Xiangfei' grape was selected as the experimental material. Treatments were applied at two stages: full bloom and 10 – 14 d after flowering. Three plant growth regulators, gibberellin (GA_3), forchlorfenuron (CPPU), and thidiazuron (TDZ), were used at different concentrations and in various combinations. The aim was to investigate the effects of different treatments on the seedless rate and fruit quality of 'Xiangfei' grape and to identify the optimal protocol for seedlessness induction in this cultivar. [**Results**] The optimal treatment protocol was the application of GA_3 50 mg/L + TDZ 4 mg/L at full bloom, followed by clear water 10 – 14 d after full bloom. After this combined pre- and post-flowering treatment, a seedless rate of 73% was achieved. The corresponding fruit quality parameters were as follows: single berry weight, 17.64 g; longitudinal diameter, 28.94 mm; transverse diameter, 30.21 mm; fruit firmness, 8.41 N/cm^2; and soluble protein content, 0.94 mg/g. Compared with other treatments, this protocol improved berry longitudinal and transverse diameters, fruit firmness, single berry weight, soluble solid content, and soluble protein content in 'Xiangfei' berries. It also altered the fruit shape index, reduced tannin content, and had a minimal impact on vitamin C content. [**Conclusions**] This study can provide a theoretical basis and technical reference for the seedlessness production of 'Xiangfei' grape.

Key words Gibberellin; Forchlorfenuron; Thidiazuron; 'Xiangfei'; Seedlessness; Quality

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With the rapid development of China's table grape industry, seedless grapes have become key players in both the fresh grape and raisin markets due to their convenient consumption and high economic value. As a result, inducing seedlessness in grapes through cultivation techniques has emerged as a major trend in the development of grape industry[1]. In practical production, to obtain seedless grapes, aside from cultivating seedless varieties, plant growth regulators can also be applied to induce pollen abortion, abnormal embryo sac differentiation, or inhibited seed development in seeded grapes, thereby forming seedless fruits[2]. Natural seedless varieties may not meet consumer demands for flavor and appearance due to varietal limitations. Additionally, since these seedless varieties lack the gibberellin stimulation produced by seeds, their fruits are generally smaller compared with conventional seeded varieties. Therefore, plant growth regulators are often applied to further optimize quality characteristics such as fruit size, shape, and ripening time, thereby enhancing their market competitiveness.

Gibberellin (GA_3), clopyridium (CPPU) and thidiazuron (TDZ) are commonly used agents for inducing seedlessness in grape production. Currently, research reports on grape seedlessness treatment and fruit quality in China are increasing, playing an increasingly important role in the actual production of seedless grapes. Many experts and scholars have found that the sole application of GA_3 often leads to significant side effects, such as brittleness and distortion of the rachis[3]. Consequently, subsequent research directions have focused on combined treatments using mixed agents. For instance, GA_3, CPPU and TDZ are applied in combination. Wang *et al.*[4] discovered that the effectiveness of inducing seedlessness in 'Kyoho' grapes varies depending on the period and concentration of the chemical combinations used. The combination of GA_3 and CPPU proved significantly more effective in inducing seedlessness than individual treatments. Additionally, Zhang *et al.*[5] conducted experiments on berry enlargement and seedlessness induction in 'Shine Muscat' grapes using GA_3, CPPU, and TDZ. Their findings indicated that cluster dipping with a combination of TDZ, CPPU, and GA_3 yielded superior results. Cheng *et al.*[6] performed seedlessness trials on 'Hongyan Wuhe' grape by applying GA_3 and TDZ at different stages, and observed that the combined treatment of GA_3 and TDZ achieved relatively higher effectiveness.

The 'Xiangfei' grape is an early-maturing high-quality variety bred from a cross between 'Muscat Hamburg' × 'Shabab Pearl' as the female parent and *Vitis vinifera* 'Crimson Seedless' as the male parent. It exhibits strong disease resistance and exceptionally high-yielding ability. Given the varying sensitivity of different grape varieties to chemical agents, the application time, concentrations and treatment combinations for seedlessness-inducing agents also differ. Therefore, it is necessary to conduct in-depth research on the application time, concentrations, and combinations of plant growth regulators. At present, there are relatively

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few reports on the seedless treatment of 'Xiangfei' grape. In this study, different concentrations and combinations of gibberellin (GA_3), forchlorfenuron (CPPU) and thidiazuron (TDZ) were applied to 'Xiangfei' grape at various developmental stages, aiming to identify suitable concentrations, combinations and application time for enhancing the commercial quality of the fruit. This study provides a theoretical reference for the production of high-quality seedless grapes with large berries.

Materials and Methods

Experimental site and material

The experiment was conducted in a rain-sheltered vineyard at the Shigezhuang Grape Breeding Base in Changli County, Qinhuangdao City, Hebei Province (39°44′52″ N, 119°13′6″ E). The region has an annual average temperature of 11.3 ℃ and an average annual precipitation of 713 mm. The test materials consisted of 10-year-old 'Xiangfei' grapevines, trained in a Y-shaped double-cordon trellis system with rows oriented north – south and a planting spacing of 0.7 m × 3.0 m. Natural grass cover was maintained between rows. Fertilization, irrigation and pest control were carried out according to conventional practices.

The test agents included gibberellin (GA_3, 90% active ingredient), forchlorfenuron (CPPU, 98% active ingredient), and thidiazuron (TDZ, 90% active ingredient). All agents were produced by Beijing Boaotoda Technology Co., LTD.

Plants with moderate vigor and uniform growth were selected as test subjects and labeled. After inflorescence separation, pruning and training were performed to remove lateral clusters. Fifteen treatment groups were established for this experiment, with clear water serving as the CK. Each treatment group consisted of 10 inflorescences, and was repeated three times (specific details are provided in Table 1). The experiment was conducted in two phases. The first phase was carried out in the full bloom stage (May 23, 2024), when inflorescences were dipped in solutions of varying concentrations and combinations of gibberellin (GA_3), forchlorfenuron (CPPU), and thidiazuron (TDZ). The second phase took place 10 to 14 d after flowering (June 4, 2024), during which inflorescences were treated by dipping in a mixed solution of GA_3 at a concentration of 50 mg/L and TDZ at 4 mg/L, or in clear water. The dipping time for each treatment was 15 s. The experiment was arranged in a completely randomized design, with individual plants serving as plots. Sampling was conducted with three replications.

Seedless rate determination

After the fruits matured, six clusters were randomly collected from each treatment. From each cluster, fruits were selected from the upper, middle, and lower sections, and 10 berries of similar size were chosen from each section, resulting in a total of 30 berries per cluster. Each grape berry was dissected to examine the presence of seeds, and the seedless rate was subsequently calculated.

Seedless rate (%) = (Number of seedless berries/Total number of berries) × 100%

Determination of fruit external quality

Sampling followed the principle of random selection. Three fruit clusters under the same treatment condition were randomly chosen, and the length of each cluster was measured. Additionally, 30 berries were randomly selected from the upper, middle, and lower sections of the clusters. The weight of single berry and the longitudinal and transverse diameters of the berries were measured, and fruit shape index was calculated based on these measurements.

Table 1 Seedless treatment scheme for 'Xiangfei' grape

Treatment	Flowering stage (t1)	10 – 14 d after flowering (t2)
CK	Clear water	Clear water
T_1	GA_3 20 mg/L	Clear water
T_2	GA_3 50 mg/L	Clear water
T_3	GA_3 80 mg/L	Clear water
T_4	GA_3 20 mg/L	GA_3 50 mg/L + TDZ 4 mg/L
T_5	GA_3 50 mg/L	GA_3 50 mg/L + TDZ 4 mg/L
T_6	GA_3 80 mg/L	GA_3 50 mg/L + TDZ 4 mg/L
T_7	GA_3 20 mg/L + CPPU 8 mg/L	Clear water
T_8	GA_3 50 mg/L + CPPU 8 mg/L	Clear water
T_9	GA_3 80 mg/L + CPPU 8 mg/L	Clear water
T_{10}	GA_3 20 mg/L + CPPU 8 mg/L	GA_3 50 mg/L + TDZ 4 mg/L
T_{11}	GA_3 50 mg/L + CPPU 8 mg/L	GA_3 50 mg/L + TDZ 4 mg/L
T_{12}	GA_3 80 mg/L + CPPU 8 mg/L	GA_3 50 mg/L + TDZ 4 mg/L
T_{13}	GA_3 50 mg/L + TDZ 4 mg/L	Clear water
T_{14}	Clear water	GA_3 50 mg/L + TDZ 4 mg/L
T_{15}	Clear water	GA_3 50 mg/L

Determination of fruit internal quality

Sampling was conducted following the principle of random selection. The measurements included fruit firmness, as well as the contents of soluble solids, soluble protein, soluble sugars, titratable acids, vitamin C, and tannin. The sugar-to-acid ratio was calculated based on these measurements.

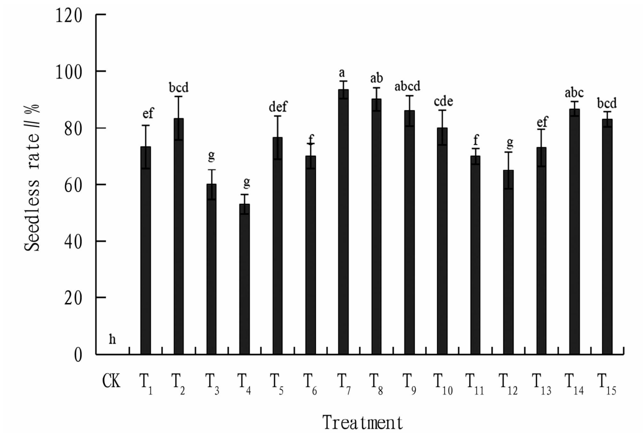
Data processing and analysis

After preliminary data processing was completed using Excel software, data analysis was conducted with the DPS data processing system. Finally, Duncan's new multiple range test (SSR) was applied to analyze the significance of differences.

Results and Analysis

Effects of different drug treatment combinations on seedlessness in 'Xiangfei' grape

As can be inferred from Fig. 1, all treatments increased the seedless rate of the grape, though certain differences were observed among various treatments. Among them, T_7 (t1: GA_3 20 mg/L + CPPU 8 mg/L, t2: clear water) achieved the highest seedless rate at 93.33%, followed by T_8 at 90%, and T_{14} at 86.67%. Furthermore, among all treatments, the lowest seedless rate was observed in T_4, at only 53%, showing significant differences. The comprehensive experimental results indicated that seedlessness treatments applied at full bloom and 10 – 14 d after flowering could effectively enhance the seedless rate in 'Xiangfei' grape.



Letters are used to indicate that there are significant differences at the level of 5% significance (the same below).

Fig. 1 Effects of different treatments on seedlessness in 'Xiangfei' grape

Effects of different treatments on the external quality of 'Xiangfei' grape

As shown in Table 2, with the increase in GA_3 concentration from T_1 to T_3, the transverse diameter of fruit showed a decreasing trend. The largest transverse diameter of fruit was observed in T_{13} at 28.94 mm, followed by T_6 at 28.04 mm. Compared with the CK, T_{13} and T_6 significantly increased the transverse diameter by 11.14% and 7.68%, respectively. Except for T_6, T_{13} and T_{15}, the fruit transverse diameter of other treatments did not differ significantly from that of the CK. The longitudinal diameter of fruit was greatest in T_{13} (30.21 mm), which represented a significant increase of 11.39% compared with the CK and showed significant differences from other treatments. The smallest longitudinal diameter was observed in T_{15} (26.88 mm), which was 0.88% lower than the CK. Compared with the CK, all treatments except T_{15} promoted the growth in the longitudinal diameter of fruit to varying degrees, indicating that that different treatments led to changes in the shape of fruit grains to different degrees. The fruit shape index of 'Xiangfei' grape ranged from 1.00 to 1.15. In particular, treatment T_3 resulted in the highest fruit shape index, reaching 1.15, which was significantly higher than that of other treatments.

The fruit cluster length in all treatment groups was greater than that of the CK, indicating that the applied treatments positively contributed to cluster elongation. The greatest cluster length was observed in the T_2 treatment, measuring 25.75 cm, followed by T_{15} at 25.03 cm. Compared with the CK, T_2 and T_{15} significantly increased cluster length by 30.71% and 27.06%, respectively. In terms of single berry weight, by comparing the effects of treatments T_2 and T_{15}, the application of GA_3 at 50 mg/L during full bloom combined with concentration-based treatments 10 – 14 d after full bloom could enhance single berry weight. Among various treatments, T_{13} achieved the highest single berry weight at 17.64 g, representing a 43.65% increase compared with the CK. It was followed by T_6 with a single berry weight of 15.14 g, which was 23.29% higher than the CK.

Table 2 Effects of different treatments on the appearance quality of 'Xiangfei' grape

Treatment	Longitudinal diameter of fruit // mm	Tranverse diameter of fruit // mm	Shape index	Fruit cluster length // cm	Single berry weight // g
CK	27.12 ± 1.28 c	26.04 ± 1.52 cde	1.04 ± 0.05 def	19.70 ± 1.47 c	12.28 ± 1.29 ef
T_1	29.70 ± 1.29 a	27.63 ± 0.75 abc	1.08 ± 0.05 bcde	21.20 ± 1.97 bc	14.28 ± 1.05 bcd
T_2	28.70 ± 1.27 abc	26.36 ± 1.33 bcde	1.09 ± 0.05 abcd	25.75 ± 2.42 a	12.84 ± 1.03 de
T_3	29.29 ± 1.18 ab	25.58 ± 0.75 def	1.15 ± 0.04 a	23.93 ± 2.90 ab	13.75 ± 0.99 bcde
T_4	29.45 ± 1.03 ab	27.14 ± 0.10 abcde	1.09 ± 0.04 abcde	23.13 ± 3.12 abc	14.38 ± 1.51 bcd
T_5	29.72 ± 2.03 a	26.28 ± 1.35 bcde	1.13 ± 0.07 ab	22.63 ± 2.63 abc	13.93 ± 1.53 bcde
T_6	28.61 ± 1.37 abc	28.04 ± 1.44 ab	1.02 ± 0.04 ef	21.90 ± 2.12 abc	15.14 ± 1.76 b
T_7	27.56 ± 0.43 bc	27.47 ± 1.14 abcd	1.00 ± 0.03 f	24.10 ± 2.17 ab	13.18 ± 1.33 cde
T_8	29.06 ± 1.58 ab	27.05 ± 1.27 bcde	1.08 ± 0.05 bcde	21.28 ± 1.93 bc	13.73 ± 1.25 bcde
T_9	29.08 ± 0.99 ab	27.87 ± 1.29 abc	1.05 ± 0.05 def	23.15 ± 1.64 abc	14.73 ± 1.34 bc
T_{10}	28.59 ± 1.45 abc	26.91 ± 1.88 bcde	1.06 ± 0.06 cdef	23.18 ± 3.19 abc	13.34 ± 2.02 bcde
T_{11}	29.14 ± 0.96 ab	26.58 ± 1.14 bcde	1.10 ± 0.05 abcd	22.98 ± 2.23 abc	14.02 ± 0.80 bcde
T_{12}	28.57 ± 1.37 abc	25.41 ± 1.30 ef	1.13 ± 0.04 abc	21.43 ± 0.87 bc	12.30 ± 1.13 ef
T_{13}	30.21 ± 2.27 a	28.94 ± 2.25 a	1.04 ± 0.01 def	21.83 ± 3.38 abc	17.64 ± 0.43 a
T_{14}	28.68 ± 1.54 abc	27.21 ± 1.82 abcde	1.06 ± 0.06 def	22.70 ± 1.53 abc	14.20 ± 2.13 bcd
T_{15}	26.88 ± 1.53 c	23.92 ± 1.63 f	1.13 ± 0.06 abc	25.03 ± 2.43 ab	10.78 ± 1.53 f

Effects of different treatments on the internal quality of 'Xiangfei' grape

All treatments improved berry firmness to varying degrees. As shown in Table 3, among all treatments, T_{13} (t1: GA_3 50 mg/L + TDZ 4 mg/L, t2: clear water) resulted in the highest berry firmness, measuring 8.41 N/cm^2. Compared with the CK, the T_5 (t1: GA_3 50 mg/L, t2: GA_3 50 mg/L + TDZ 4 mg/L) treatment significantly reduced the conten of soluble solids in the fruit by 2.05%. In contrast, T_{10} achieved the highest content of soluble solids at 17.38%, representing a significant increase of 8.08% compared with the CK.

Among all treatments, the soluble sugar content in T_3 and T_4 was significantly higher than that in the CK, exceeding it by 36.18% and 29.41%, respectively. The differences between other treatments were not significant. Compared with the CK, the soluble sugar content in T_7 decreased by 4.24%, while in T_{10}, it increased by 2.07%. The soluble sugar content was lowest in T_2, which was 30.46% lower than the CK. Regarding titratable acid content, it could be observed that, except for T_2, T_3, T_4, and T_{14}, which showed clear differences from the CK, other treatments exhibited no significant differences. Specifically, T_5 had the highest titratable acid content at 0.59%, while T_{14} had the lowest at 0.36%.

As shown in Table 3, all treatments increased the soluble protein content of the fruit to varying degrees. Among them, T_{13} exhibited the highest soluble protein content at 0.94 mg/g, while T_7 showed the lowest at 0.22 mg/g, representing a decrease of 0.24 mg/g compared with the CK. In terms of tannin content, T_5 had the highest tannin content at 3.47%, showing an increase of 1.82% compared with the CK. T_9 had the lowest tannin content at 0.65%, and T_{13} (0.95%) showed a reduction in tannin content compared with the CK. Regarding vitamin C content, except for T_1 and T_6, all other treatments showed a decrease in vitamin C content compared with the CK, indicating minimal impact on vitamin C levels. Among them, T_6 and T_1 relatively increased the vitamin C content of the fruit. Regarding the sugar-to-acid ratio, it could be observed that as the concentration of the GA_3 and CPPU mixture increased from T_7 to T_9, the sugar-to-acid ratio showed an upward trend. Compared with the CK, T_3 had the highest sugar-to-acid ratio at 47.61, representing an increase of 81.44%, followed by T_4 with a sugar-to-acid ratio of 43.99, showing an increase of 67.64%.

Table 3 Effects of different treatments on the internal quality of 'Xiangfei' grape

Treatment	Fruit firmness N/cm^2	Soluble solids // %	Soluble sugars // %	Titratable acids // %	Soluble protein // mg/g	Tannin (gallotannic acid) // %		
CK	6.06 ± 1.04 d	16.08 ± 0.78 bcd	15.20 ± 0.80 cd	0.58 ± 0.04 ab	0.46 ± 0.10 cde	1.65 ± 0.48 defgh	6.60 ± 0.51 bc	26.24 ± 0.42 def
T_1	8.24 ± 1.12 abc	16.1 ± 0.84 bcd	13.31 ± 1.55 de	0.46 ± 0.02 bcde	0.57 ± 0.16 bcd	1.79 ± 0.60 defg	7.69 ± 0.51 ab	28.96 ± 2.24 cdef
T_2	8.03 ± 1.96 abc	16.68 ± 0.73 abcd	10.57 ± 1.86 e	0.45 ± 0.08 cde	0.74 ± 0.14 ab	2.28 ± 0.33 cd	6.12 ± 0.20 c	23.65 ± 0.33 f
T_3	7.83 ± 1.99 abcd	16.03 ± 0.86 cd	20.70 ± 0.59 a	0.43 ± 0.01 de	0.30 ± 0.07 e	0.70 ± 0.20 i	4.08 ± 0.41 ef	47.61 ± 1.36 a
T_4	7.99 ± 0.65 abc	15.87 ± 0.56 cd	19.67 ± 2.17 ab	0.45 ± 0.02 cde	0.45 ± 0.07 cde	2.03 ± 0.72 cdef	2.86 ± 0.97 fg	43.99 ± 3.83 ab
T_5	6.15 ± 1.54 d	15.75 ± 0.76 d	14.90 ± 3.47 cd	0.59 ± 0.12 a	0.73 ± 0.11 ab	3.47 ± 0.87 a	4.22 ± 0.62 ef	25.13 ± 2.26 ef
T_6	7.53 ± 1.12 abcd	16.13 ± 0.79 bcd	14.36 ± 3.68 cde	0.47 ± 0.04 abcde	0.34 ± 0.08 de	3.24 ± 0.39 ab	8.16 ± 0.41 a	30.56 ± 7.82 cdef
T_7	6.56 ± 2.29 bcd	16.43 ± 1.05 abcd	10.96 ± 1.12 e	0.47 ± 0.04 abcde	0.22 ± 0.08 e	0.87 ± 0.34 hi	3.67 ± 1.47 ef	23.42 ± 3.59 f
T_8	8.32 ± 1.18 abc	17.17 ± 0.59 a	14.03 ± 1.46 cde	0.51 ± 0.10 abcd	0.60 ± 0.17 bc	2.22 ± 0.33 cde	3.61 ± 0.47 ef	28.53 ± 7.37 cdef
T_9	6.48 ± 0.89 cd	16.47 ± 0.77 abcd	17.58 ± 1.99 abc	0.53 ± 0.06 abcd	0.62 ± 0.08 bc	0.65 ± 0.23 i	5.64 ± 1.07 cd	33.14 ± 2.56 cdef
T_{10}	8.13 ± 1.05 abc	17.38 ± 0.65 a	17.27 ± 2.49 abc	0.46 ± 0.02 bcde	0.65 ± 0.28 bc	1.54 ± 0.25 defgh	3.97 ± 0.49 ef	37.79 ± 6.62 bc
T_{11}	7.23 ± 1.15 abcd	17.28 ± 0.69 a	13.25 ± 2.19 de	0.57 ± 0.12 abc	0.75 ± 0.10 ab	1.41 ± 0.08 efghi	3.40 ± 0.96 efg	23.60 ± 2.67 f
T_{12}	6.50 ± 1.18 cd	16.92 ± 0.86 abc	15.52 ± 1.82 cd	0.48 ± 0.11 abcde	0.82 ± 0.19 ab	2.62 ± 0.16 bc	2.18 ± 0.42 g	34.05 ± 12.77 cde
T_{13}	8.41 ± 1.30 a	15.98 ± 0.62 cd	16.51 ± 2.38 bcd	0.50 ± 0.02 abcd	0.94 ± 0.13 a	0.95 ± 0.23 ghi	4.31 ± 0.62 e	33.28 ± 3.74 cdef
T_{14}	8.39 ± 0.79 ab	16.75 ± 0.98 abcd	12.67 ± 0.88 de	0.36 ± 0.01 e	0.74 ± 0.09 ab	1.33 ± 0.46 fghi	4.44 ± 0.94 de	34.99 ± 2.43 cd
T_{15}	8.23 ± 1.04 abc	17.10 ± 0.59 ab	13.85 ± 1.19 cde	0.53 ± 0.04 abcd	0.58 ± 0.08 bcd	1.64 ± 0.57 defgh	4.52 ± 0.46 de	26.23 ± 3.72 def

Comprehensive evaluation of seedlessness treatment indicators

As shown in Table 4, principal component analysis was conducted on 13 fruit quality indicators of 'Xiangfei' grape. Following the criterion of eigenvalues greater than 1, five principal components were extracted. The cumulative contribution rate reached 81.74%, indicating that these components represented the majority of the information from the original data. It demonstrated that these five sets of principal components could effectively characterize the information related to seedlessness treatment indicators.

Table 4 Characteristic roots of 'Xiangfei' grape and principal component index of its contribution rate

Pricipal component	Eigen values	Contribution rate // %	Cumulative contribution rate // %
PC_1	3.42	26.28	26.28
PC_2	2.33	17.90	44.17
PC_3	1.87	14.36	58.53
PC_4	1.74	13.34	71.87
PC_5	1.28	9.87	81.74

As can be inferred from Table 5, scoring models for the five principal components could be constructed based on the principal component loading matrix (Table 5). In the models, P_1 to P_5 represent the scores of each principal component for the grape under different treatment conditions, X_1 to X_{13} respectively represent the 13 distinct quality indicators, and P corresponds to the respective comprehensive scores, specifically:

$$PC_1 = 0.92X_1 + 0.79X_2 + 0.10X_3 - 0.33X_4 + 0.96X_5 + 0.15X_6 - 0.44X_7 + 0.11X_8 - 0.10X_9 + 0.11X_{10} + 0.28X_{11} - 0.11X_{12} + 0.16X_{13}$$

$$PC_2 = -0.13X_1 + 0.30X_2 + 0.30X_3 - 0.09X_4 + 0.14X_5 + 0.05X_6 - 0.28X_7 + 0.96X_8 - 0.17X_9 + 0.91X_{10} - 0.15X_{11} - 0.21X_{12} - 0.38X_{13}$$

$$PC_3 = 0.09X_1 + 0.09X_2 + 0.15X_3 + 0.45X_4 + 0.08X_5 + 0.88X_6 + 0.28X_7 - 0.08X_8 - 0.83X_9 + 0.35X_{10} - 0.001X_{11} - 0.22X_{12} + 0.13X_{13}$$

$$PC_4 = -0.10X_1 + 0.19X_2 + 0.86X_3 - 0.41X_4 + 0.02X_5 + 0.14X_6 - 0.07X_7 + 0.06X_8 + 0.20X_9 - 0.05X_{10} + 0.39X_{11} + 0.64X_{12} + 0.45X_{13}$$

$$PC_5 = -0.18X_1 + 0.23X_2 + 0.21X_3 + 0.14X_4 - 0.01X_5 + 0.17X_6 + 0.62X_7 - 0.03X_8 + 0.16X_9 - 0.07X_{10} + 0.80X_{11} - 0.07X_{12} - 0.69X_{13}$$

The principal component scores were calculated individually, with weights assigned based on the relative variance contribution rates of each principal component. The weighted sum of the principal component scores was then computed to construct a comprehensive evaluation model.

$$PC = 2.60PC_1 + 1.25PC_2 + 1.37PC_3 + 2.32PC_4 + 1.28PC_5$$

Ranking was performed according to the resulting scores.

Table 5 Factor load matrix of evaluation index of 'Xiangfei' grape seedless treatment

Code	Seedless treatment indicators	Principal component				
		PC_1	PC_2	PC_3	PC_4	PC_5
X_1	Transverse diameter of fruit	0.92	-0.13	0.09	-0.10	-0.18
X_2	Longitudinal length of fruit	0.79	0.30	0.09	0.19	0.23
X_3	Shape index	0.10	0.30	0.15	0.86	0.21
X_4	Cluster length	-0.33	-0.09	0.45	-0.41	0.14
X_5	Single berry weight	0.96	0.14	0.08	0.02	-0.01
X_6	Fruit hardness	0.15	0.05	0.88	0.14	0.17
X_7	TSS	-0.44	-0.28	0.28	-0.07	0.62
X_8	Soluble sugar	0.11	0.96	-0.08	0.06	-0.03
X_9	Titratable acid	-0.10	-0.17	-0.83	0.20	0.16
X_{10}	Sugar-acid ratio	0.11	0.91	0.35	-0.05	-0.07
X_{11}	Soluble protein	0.28	-0.15	-0.001	0.39	0.80
X_{12}	Tannin	-0.11	-0.21	-0.22	0.64	-0.07
X_{13}	Vitamin C	0.16	-0.38	0.13	0.45	-0.69

Comprehensive scores of principal components The results of the principal component analysis are presented in Table 6. The comprehensive scores reflected the quality advantages and disadvantages of various treatments. After ranking the PC values, the order from highest to lowest was $T_{13} > T_4 > T_3 > T_{14} > T_1 > T_{10} > T_9 > T_6 > T_8 > T_{11} > T_2 > T_5 >$ CK $> T_{15} > T_7$. Among the seedlessness treatments for 'Xiangfei' grape, T_{13} achieved the highest comprehensive score. It indicated that applying GA_3 50 mg/L + TDZ 4 mg/L at full bloom, followed by clear water 10–14 d after flowering, yielded the best overall improvement in the comprehensive quality of 'Xiangfei' grape.

Table 6 Comprehensive score and ranking of 'Xiangfei' grape with different treatment methods

Treatment	PC_1	PC_2	PC_3	PC_4	PC_5	Comprehensive score	Ranking
CK	0.80	0.22	0.51	1.70	0.14	0.69	14
T_1	2.14	0.37	1.03	1.87	0.36	1.30	5
T_2	1.01	0.32	1.23	1.55	1.01	0.99	12
T_3	1.45	2.11	1.34	0.94	0.44	1.37	3
T_4	1.90	1.85	1.11	1.35	0.64	1.51	2
T_5	1.58	0.36	0.48	1.99	0.78	1.66	13
T_6	1.87	0.33	0.69	2.01	0.09	1.14	8
T_7	0.75	0.31	0.35	0.07	0.21	0.41	16
T_8	1.39	0.36	0.90	1.65	1.27	1.11	9
T_9	1.83	0.91	0.40	1.30	0.71	1.16	7
T_{10}	1.19	0.96	1.34	1.34	1.32	1.21	6
T_{11}	1.20	0.05	0.41	1.40	1.56	0.89	10
T_{12}	0.80	0.71	0.24	1.58	1.42	0.88	11
T_{13}	3.11	1.11	1.09	1.68	1.15	1.85	1
T_{14}	1.63	0.60	1.69	1.36	1.09	1.31	4
T_{15}	0.28	0.00	0.94	1.23	1.19	0.60	15

Conclusions and Discussion

'Xiangfei' grape is a high-quality early-maturing variety, and the application of growth regulators can enhance its seedless rate and commercial value. Different concentrations of GA_3 combined with CPPU, as well as combinations of GA_3 and TDZ, can induce seedlessness in 'Xiangfei' grape to varying degrees[7]. Studies have shown that the initial treatment can induce fruit seedlessness, with the time of this first treatment being critical for achieving effective seedlessness control, while the second treatment aids in promoting fruit enlargement. If treatments are applied either too early or too late, the desired outcomes may not be achieved[8-9]. According to the results of this study, the lowest seedless rate of 60% was observed under the treatment t1: GA_3 80 mg/L, t2: clear water. In contrast, the highest seedless rate of 93.33% was achieved under the treatment t1: GA_3 20 mg/L + CPPU 8 mg/L, t2: clear water. Commonly used agents for grape seedlessness induction primarily include GA_3, supplemented by CPPU, TDZ, and others. The combined use of these agents yields more favorable seedlessness outcomes compared with the sole application of GA_3. The experimental results are largely consistent with the findings of Zhang *et al.* [10].

In experiments on fruit enlargement of ‘Wuhe Cuibao’ grape using GA_3 and CPPU, treatments with GA_3 combined with different concentrations of CPPU significantly increased fruit weight, fruit transverse and longitudinal diameters, and the fruit shape index compared with the CK. Similarly, in this study, treatments with varying concentrations of GA_3 and CPPU applied at full bloom in ‘Xiangfei’ grape enhanced fruit weight, transverse and longitudinal diameters, cluster length, and fruit shape index to varying degrees. These findings are largely consistent with the research results of Lyu *et al.* [11] on ‘Wuhe Cuibao’ grape. The primary reason lies in the synergistic effect of CPPU and GA_3 in promoting cell expansion[12]. This outcome aligns with the results observed in treatments for ‘Zaosexiang’ and ‘Summer Black’ grapes[13-14]. Fruit firmness exerts a relatively significant influence on flesh texture and can serve as a key parameter for evaluating grape flesh texture[15]. In this study, different treatment combinations of GA_3 with CPPU and GA_3 with TDZ were able to enhance the firmness of ‘Xiangfei’ berries. These findings are largely consistent with the experimental results reported by Guo *et al.* [16] in their treatment of ‘Wuhe Cuibao’ grape. The increased fruit firmness resulting from the treatments enhanced the fruit's tolerance to storage and transportation, thereby improving its commercial value. It also helped maintain the crisp and tender texture of grapes, enhancing consumers' eating experience.

Key indicators for evaluating the internal quality of fruit typically include soluble sugars, soluble solids, protein, and titratable acid content. The effectiveness of plant growth regulators can vary depending on factors such as region, climate, variety, tree condition, and application techniques, and may even yield contradictory results[17]. In this study, the combined application of GA_3 with CPPU and GA_3 with TDZ resulted in a reduction in tannin content while also leading to a certain degree of decrease in the content of soluble solids compared with the CK. It might be attributed to the increase in fruit setting rate and cluster weight, as well as greater single berry weight following the treatments, which could have led to insufficient nutrient supply. The treatments of GA_3 + CPPU and GA_3 + TDZ had minimal impact on the vitamin C content of ‘Xiangfei’ berries, which is relatively consistent with the experimental results reported by Liu *et al.* [18]. This might be due to the influence by factors such as soil type, climatic conditions, and light intensity. Additionally, harvesting too early or too late can also affect the vitamin C content. The measurement results for the ‘Xiangfei’ variety showed that its acid content ranged from 0.36% to 0.59%. This relatively small variation indicated that the titratable acid content in the treated samples was relatively stable.

Through a comprehensive analysis comparing the seedless rate, external quality, and internal quality of ‘Xiangfei’ berries, it was concluded that the treatment t1: GA_3 50 mg/L + TDZ 4 mg/L for cluster dipping at full bloom, followed by t2: clear water for berry dipping 10 - 14 d after flowering, yielded the best overall quality with a seedless rate of 73%. This approach can serve as a reference for seedlessness induction in ‘Xiangfei’ grape production.

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