Effect of Various Citrus Rootstock-scion Combinations on Tree Growth, Fruit Quality, and Photosynthetic Characteristics under Red Loam Soil Conditions

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Abstract [**Objectives**] To investigate the effects of 15 distinct citrus rootstock-scion combinations on tree growth, fruit quality, and photosynthetic characteristics under red loam soil conditions and provide a theoretical foundation for the selection of appropriate citrus rootstock-scion combinations in the Zhaoqing region. [**Methods**] A total of 15 citrus rootstock-scion combinations were utilized as test materials for a comprehensive analysis of their phenological periods (budding, flowering, and fruiting), tree growth indicators (tree height, crown diameter, and growth), and fruit quality (appearance quality and intrinsic quality). The photosynthetic characteristics of the test materials, including the net photosynthetic rate (Pn), transpiration rate (Tr), water use efficiency (WUE), apparent quantum yield (AQY), and carboxylation efficiency (CE), were analyzed to determine their significance. Additionally, the leaf photosynthetic physiological indicators, such as soluble protein, specific leaf weight, chlorophyll, and carotenoids, were evaluated. [**Results**] There were notable differences observed in the phenological period, growth potential of trees, fruit quality, and photosynthetic characteristics among various citrus rootstock-scion combinations. The phenological periods exhibited variation contingent on the grafting varieties. In terms of tree growth potential, the *Citrus tangerina* Tanaka 'Hongju' and *C. haniana* Hort. 'Suanju' rootstocks demonstrated greater tree height, crown growth, and overall tree strength; however, they were also prone to excessive growth. Conversely, the *C. limonia* Osbeck 'Hongningmeng' and *C. sinensis* × *P. trifoliata* 'Zhicheng' rootstocks displayed medium growth potential, while the *Poncirus trifoliate* (L) Raf. 'Zhike' rootstock resulted in shorter trees. In terms of fruit quality, the single fruit weight of *C. flamea* Hort. 'Shatangju' ranged from 33 to 50 g, exhibiting a flat and round shape. The total soluble solids and titratable acid content of 'Shatangju' grafted onto the 'Zhike' rootstock were notably high. In contrast, the single fruit weight of *C. haniana* Hort. 'Chuntianju' varied between 65 and 81 g, characterized by a high flat round shape. The 'Suanju' rootstock demonstrated a higher sugar and acid content compared to other rootstocks. Additionally, the single fruit weight of *C. nobilis* Lour. 'Gonggan' ranged from 62 to 145 g, with the fruit shape being either round or oval. The soluble sugar and total soluble solids content associated with the 'Zhike' rootstock was also elevated. In relation to photosynthetic characteristics, the photosynthetic performance of the 'Shatangju' variety was superior when grafted onto the 'Zhike' and 'Hongju' rootstocks. Similarly, the 'Chuntianju' variety exhibited enhanced photosynthetic performance on the 'Zhike', 'Zhicheng', and 'Hongju' rootstocks. Furthermore, the 'Gonggan' variety demonstrated improved photosynthetic performance when grafted onto the 'Zhike' and 'Suanju' rootstocks. [**Conclusions**] Based on the characteristics of the red loam soil in the Zhaoqing region, the rootstocks 'Zhike' and 'Hongju' are conducive to the cultivation of the 'Shatangju' variety. Additionally, the rootstocks 'Zhike', 'Zhicheng', and 'Hongju' are optimal for the growth of the 'Chuntianju' variety, while the rootstocks 'Zhike' and 'Suanju' are appropriate for the growth of the 'Gonggan' variety.

Key words Citrus, Rootstock-scion, Tree growth, Fruit quality, Photosynthetic characteristics

1 Introduction

The Xijiang River Basin in Guangdong Province, as a high-quality development belt for the citrus industry, mainly concentrates on the cultivation of varieties such as *Citrus flamea* Hort. ex Tseng. 'Shatangju' and *C. nobilis* Lour. 'Gonggan'[1]. Zhaoqing, recognized as the origin of citrus varieties such as 'Shatangju' and 'Gonggan', possesses a rich history of cultivation and is considered one of the primary production regions in Guangdong Province. The citrus industry plays a crucial role in the local agricultural economy and is of considerable importance for the successful implementation of the rural revitalization strategy. With the advancement of the social economy and the enhancement of living standards, traditional citrus varieties are unable to fully satisfy market demand. In recent years, Zhaoqing has been dedicated to advancing the standardization and scaling of the cultivation of 'Shatangju' and 'Gonggan'. This initiative includes the introduction of new citrus varieties, such as *Citrus haniana* Hort. 'Chazhigan', *C. medical* L. 'Xiangshuiningmeng', and *C. haniana* Hort. 'Chuntianju', which are selected based on the specific geographical and environmental characteristics of the re-

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gion. Furthermore, efforts are being made to enhance both the yield and quality of citrus fruits by optimizing the varietal structure, thereby improving the market competitiveness of the industry. Red loam soils, which are extensively distributed throughout Guangdong, are especially prevalent in Zhaoqing. According to survey data, the soil type utilized for the cultivation of 'Shatangju' is predominantly composed of clayey red loam soils, which constitute approximately 72.22% of the area[2]. A comprehensive multi-angle systematic investigation of citrus rootstock-scion combinations under red loam soil conditions in Zhaoqing holds significant theoretical value for practical applications in production. Relevant studies have demonstrated that the choice of rootstock species significantly influences the horticultural traits of citrus scions. This influence can regulate plant growth and development, ultimately affecting both fruit yield and quality[3]. Under identical ecological conditions, various combinations of citrus rootstocks and scions exhibit notable differences in terms of tree vigor and fruit quality[4]. When grafting the variety 'Asumi' onto three different rootstocks, including *C.* × *junos* Siebold ex Tanaka 'Xiangcheng', *Poncirus trifoliate* (L.) Raf. 'Zhike', and *C. tangerina* Tanaka 'Hongju', it was determined that 'Xiangcheng' and 'Zhike' were the most suitable rootstock options for 'Asumi'[5]. Through an analysis of the performance of 'Ehime Kashi No. 28' mandarin grafted onto various rootstocks and interstocks, it was determined that the grafting efficacy of *C. sinensis* (L.) Osbeck 'Ziyang Xiangcheng' rootstock surpassed that of the other rootstocks examined[6]. Liu Yaoxin *et al.*[4] conducted a study on various grafting rootstocks for *C. reticulata* Lour. 'Wogan' and determined that 'Ziyang Xiangcheng' was the most appropriate rootstock for this variety. A total of 10 distinct rootstocks were employed in grafting trials on 'Shatangju' to investigate various related indicators, including plant height, yield, and quality. Ultimately, three rootstocks were identified as suitable for 'Shatangju' cultivation in Guangdong: *C. limonia* Osbeck 'Honglimeng', 'Xiangcheng', and *C.* × *limon* cv. Ponderosa 'Cuningmeng'[7]. Cai Yongxi *et al.*[8] identified trifoliate orange as an optimal rootstock for grafting 'Ehime Kashi No. 28,' particularly recommending its promotion in the Yidu region. Liu Zhen *et al.*[9] demonstrated that the fruit quality of 'Shatangju' grafted onto the 'Zhike' rootstock exceeded that of other rootstocks. This finding suggests that 'Zhike' is an optimal rootstock selection for the primary production regions of 'Shatangju' in Guangdong Province. *C. junos* Sieb. ex Tanaka cv. 'Pujiang Xiangcheng' rootstock was grafted onto 10 distinct citrus varieties. The findings indicated that the 'Pujiang Xiangcheng' rootstock exhibited a strong affinity with various citrus cultivars, demonstrated significant growth potential, and displayed a high net photosynthetic rate in its photosynthetic characteristics[10]. These attributes suggest its potential for widespread adoption and cultivation. While the existing research literature on citrus rootstock-scion combinations is comprehensive, there is a notable absence of systematic assessments that focus specifically on these combinations in red loam soil in Zhaoqing. The objective of this study was to systematically assess 15 distinct citrus rootstock-scion combinations, which holds significant practical relevance in the domain of citrus production. This study investigated various citrus rootstock-scion combinations, focusing on the differences in quality, tree growth potential, and photosynthetic characteristics among three types of scions ('Shatangju', 'Gonggan', and 'Chuntianju') grafted onto five rootstocks ('Zhike', 'Zhicheng', 'Hongju', 'Suanju', and 'Hongningmeng'). By comparing and contrasting these combinations, the research aimed to elucidate the specific performance of the 15 rootstock-scion combinations in the Zhaoqing area, thereby providing a scientific basis for the selection of rootstocks in citrus cultivation.

2 Materials and methods

2.1 Materials The experimental site was situated within a 40-mesh insect net chamber at the Institute of Pomology, Zhaoqing University, located in Zhaoqing City, Guangdong Province, China. The soil type of the experimental site was identified as clayey red loam, with a pH of 4.6. The soil exhibited the following characteristics: available phosphorus of 23.03 mg/kg, available nitrogen of 110.55 mg/kg, available potassium of 153.01 mg/kg, and organic matter of 20.68 g/kg. The rootstocks utilized in the experiment included *P. trifoliate* (L) Raf. 'Zhike', *C. sinensis* × *P. trifoliata* 'Zhicheng', *C. limonia* Osbeck 'Hongningmeng', *C. haniana* Hort. 'Suanju', and *C. tangerina* Tanaka 'Hongju'. The scions tested comprised *C. flamea* Hort. 'Shatangju', *C. nobilis* Lour. 'Gonggan', and *C. haniana* Hort. 'Chuntianju'. Each citrus rootstock-scion combination was planted with three individual plants. Following a two-year period of grafting and cultivation, the phenological periods of the test trees were monitored. Additionally, various indicators such as growth potential, fruit quality, and photosynthetic characteristics were assessed. The experiments were conducted three times, utilizing a single plant as the experimental plot.

2.2 Methods

2.2.1 Observation of phenological periods. The various growth stages, including the budding stage, sprouting stage, flowering stage, and ripening stage, were observed and documented.

2.2.2 Measurement of tree growth potential. Following the maturation of the spring, summer, and autumn tips, the lengths of these tips were measured. For each variety, three trees were assessed, with measurements taken from 10 branches per tree. Furthermore, the height and crown diameter of each tree were recorded.

2.2.3 Determination of fruit quality. A total of 30 fruits were systematically collected from five distinct directions: east, west, south, north, and the center of each tree, for the purpose of assessing fruit quality-related indicators. The total soluble solids (TSS) content was assessed using a hand-held shade meter, while the titratable acid (TA) content was evaluated through acid-base neutralization titration. The soluble sugar content was quantified using the 3,5-dinitrosalicylic acid method. The weight of individual fruits was determined by weighing method, and the longitudinal and transverse diameters, as well as the peel thickness, were measured using vernier calipers.

2.2.4 Measurement of daily photosynthetic variation. Under natural field conditions characterized by sunny and windless weather, fully functional leaves from the outer spring tips located in the middle of the canopy were collected hourly from 8:00 to 18:00. A portable photosynthetic measurement system (LiSD, UK) was employed to assess various parameters, including the net photosynthetic rate (Pn), transpiration rate (Tr), water use efficiency (WUE), apparent quantum yield (AQY), and carboxylation efficiency (CE). For each plant, three leaves were sampled, and three replications were conducted to calculate the average values.

2.2.5 Determination of photosynthetic physiological indicators. The chlorophyll content of the leaves was quantified using spectrophotometric methods. The soluble protein content was assessed through the Thomas Brilliant Blue G-250 staining technique. Following deactivation and drying, the leaves were weighed, and the weight of the dry leaf sample per unit area was calculated to determine the specific leaf weight (SLW).

2.2.6 Data processing. Data processing and plotting were conducted using Excel 2010, while statistical analysis was performed utilizing SPSS version 20.0. Duncan's method of one-way ANOVA was employed to assess the significance of differences among the treatments.

3 Results and analysis

3.1 Observation of phenological periods of citrus across different rootstock-scion combinations The data presented in Table 1 indicate that the phenological periods of citrus across various rootstock-scion combinations exhibited minor variations; however, these differences were not statistically significant. The budding stage of 'Shatangju' on various rootstocks occurred from January 20 to March 1. The sprouting stage for spring tips was observed from March 1 to March 17, while the sprouting stage for summer tips took place from April 23 to May 12. Additionally, the sprouting stage for autumn tips was recorded from August 7 to August 29. The 'Shatangju' variety, when grafted onto the 'Hongningmeng' rootstock, demonstrated earlier onset of first flowering, full flowering, and flower abscission compared to other rootstocks. The initial physiological fruit drop of 'Shatangju' occurred between April 3 and April 27, while the subsequent physiological fruit drop took place from April 26 to May 16. The color of 'Shatangju' transitioned from turquoise to yellow in middle October and reached full ripeness from middle to late November. The initial budding stage of 'Chuntianju' on various rootstocks was observed in early February. Specifically, the sprouting stage for spring tips of 'Chuntianju' grafted onto 'Hongningmeng' rootstock commenced as early as February 18, whereas those grafted onto other rootstocks began to sprout in early March. The sprouting stage for summer tips occurred between April 25 and May 9. Furthermore, the sprouting stage for autumn tips was documented from August 7 to August 29. The initial flowering stage occurred from March 9 to March 21, followed by full flowering from March 12 to March 27. Flower abscission took place from March 22 to March 31. The initial physiological fruit drop of 'Chuntianju' occurred between April 2 and April 17, followed by a second drop from May 2 to May 15. The ripening of the fruit transpired in February and March of the subsequent year. The initial budding stage of 'Gonggan' on different rootstocks was observed between February 2 and March 6. The sprouting stage for spring tips occurred from February 20 to March 15, while the sprouting stage for summer tips was noted from April 25 to May 12. Furthermore, the sprouting stage for autumn

Table 1 Observation of phenological periods of citrus across different rootstock-scion combinations

Rootstock	Scion	Budding stage	Sprouting stage for spring tips	Initial flowering stage	Full flowering stage	Flower abscission stage	Initial physiological fruit drop	Secondary physiological fruit drop	Sprouting stage for summer tips	Sprouting stage for autumn tips	Fruit ripening stage
'Zhicheng'	'Shatangju'	02/04 – 02/22	03/14 – 03/21	03/14 – 03/16	03/17 – 03/22	03/23 – 03/27	04/03 – 04/10	05/05 – 05/10	04/26 – 05/08	08/21 – 08/29	Middle November
	'Chuntianju'	02/04 – 02/19	03/01 – 03/08	03/08 – 03/11	03/12 – 03/22	03/23 – 03/31	04/02 – 04/10	05/08 – 05/13	04/26 – 05/08	08/21 – 08/29	Early February
	'Gonggan'	02/10 – 02/26	03/04 – 03/08	03/11 – 03/16	03/17 – 03/27	03/28 – 03/31	04/15 – 04/25	05/02 – 05/09	04/25 – 04/27	08/19 – 08/26	Middle November
'Zhike'	'Shatangju'	02/25 – 03/01	03/01 – 03/06	03/14 – 03/17	03/18 – 03/22	03/23 – 03/27	04/07 – 04/18	05/10 – 05/16	04/23 – 04/28	08/21 – 08/28	Late November
	'Chuntianju'	02/10 – 02/23	03/05 – 03/10	03/19 – 03/21	03/22 – 03/27	03/28 – 03/31	04/07 – 04/17	05/10 – 05/15	04/27 – 05/09	08/21 – 08/28	Early February
	'Gonggan'	02/25 – 03/06	03/06 – 03/11	03/16 – 03/21	03/22 – 04/04	04/05 – 04/13	04/25 – 04/27	05/10 – 05/15	05/09 – 05/12	08/16 – 08/23	Middle November
'Hongju'	'Shatangju'	01/20 – 02/22	02/28 – 03/06	03/06 – 03/11	03/12 – 03/17	03/18 – 03/25	04/03 – 04/09	04/26 – 05/02	05/07 – 05/12	08/07 – 08/25	Middle November
	'Chuntianju'	02/02 – 02/22	03/05 – 03/12	03/10 – 03/15	03/16 – 03/21	03/22 – 03/28	04/06 – 04/15	05/09 – 05/12	04/25 – 05/07	08/07 – 08/25	Middle and late February
	'Gonggan'	02/20 – 03/05	03/05 – 03/15	03/06 – 03/13	03/14 – 03/21	03/22 – 03/31	04/13 – 04/20	04/25 – 05/05	04/25 – 05/07	08/13 – 08/21	Middle November
'Hongningmeng'	'Shatangju'	01/20 – 02/20	02/20 – 02/26	02/28 – 03/05	03/06 – 03/15	03/16 – 03/27	04/12 – 04/20	05/10 – 05/15	04/25 – 05/02	08/17 – 08/29	Late November
	'Chuntianju'	02/02 – 02/15	02/18 – 03/05	03/08 – 03/11	03/12 – 03/21	03/23 – 03/26	04/07 – 04/16	05/02 – 05/12	04/25 – 05/06	08/07 – 08/23	Late February
	'Gonggan'	02/02 – 02/22	02/25 – 03/08	03/09 – 03/13	03/14 – 03/22	03/23 – 03/27	04/10 – 04/20	05/02 – 05/10	05/02 – 05/09	08/15 – 08/30	Middle November
'Suanju'	'Shatangju'	01/18 – 02/21	03/01 – 03/05	03/01 – 03/05	03/06 – 03/16	03/17 – 03/26	04/13 – 04/27	05/10 – 05/17	04/27 – 05/03	08/17 – 08/29	Middle November
	'Chuntianju'	02/02 – 02/20	03/04 – 03/10	03/12 – 03/15	03/16 – 03/21	03/22 – 03/27	04/06 – 04/14	05/08 – 05/14	05/02 – 05/09	08/13 – 08/20	Middle and late February
	'Gonggan'	02/02 – 02/20	02/20 – 03/02	03/05 – 03/14	03/15 – 03/27	03/28 – 03/31	04/10 – 04/15	05/02 – 05/10	04/25 – 05/09	08/21 – 08/29	Middle November

tips was documented from August 13 to August 30. The initial flowering period was observed from March 5 to March 21, succeeded by the full flowering period, which occurred from March 14 to March 27. Flower abscission transpired between March 22 and April 13. The initial physiological fruit drop of 'Gonggan' took place from April 10 to April 27, followed by a secondary drop occurring from May 25 to May 15. The ripening of the fruit was noted in middle November.

3.2 Differential analysis of citrus trees across different rootstock-scion combinations The data presented in Tables 2 – 4 indicate variations in the growth potential of citrus trees associated with different rootstock-scion combinations, under conditions of uniform cultivation and management practices. 'Hongju', 'Suanju', and 'Hongningmeng' rootstocks demonstrated superior performance compared to 'Zhicheng' and 'Zhike' rootstocks with respect to plant height and crown diameter. These rootstocks exhibited significant tree heights, expansive crown structures, and robust growth. In contrast, all three scions grafted onto the 'Zhike' rootstock exhibited stunted growth and limited crown development.

Table 2 Effect of different rootstocks on the growth potential of 'Shatangju' trees cm

Rootstock	Plant height	Spring tip	Summer tip	Autumn tip	Crown diameter (east – west)	Crown diameter (south – north)
'Zhicheng'	160.43 ± 12.50 b	19.04 ± 1.58 a	18.66 ± 1.44 b	27.37 ± 4.36 a	122.67 ± 28.48 a	115.93 ± 27.59 ab
'Zhike'	96.93 ± 8.12 c	18.07 ± 1.78 a	8.36 ± 0.90 c	13.78 ± 1.48 b	55.47 ± 13.55 b	50.50 ± 8.85 c
'Hongju'	214.17 ± 14.68 a	18.79 ± 2.45 a	25.46 ± 1.95 a	27.86 ± 3.24 a	118.33 ± 2.40 a	153.20 ± 8.97 a
'Hongningmeng'	208.17 ± 9.96 a	20.10 ± 1.38 a	18.38 ± 1.44 b	20.71 ± 2.08 ab	145.00 ± 15.04 a	115.67 ± 12.72 ab
'Suanju'	168.47 ± 12.14 b	12.61 ± 1.95 b	17.44 ± 1.89 b	21.80 ± 1.88 ab	120.00 ± 4.16 a	96.67 ± 13.96 b

NOTE Different capital and lowercase letters in the same column indicate highly significant differences at the 0.01 level and significant differences at the 0.05 level, respectively. The same below.

Table 3 Effect of different rootstocks on the growth potential of 'Chuntianju' trees cm

Rootstock	Plant height	Spring tip	Summer tip	Autumn tip	Crown diameter (east – west)	Crown diameter (south – north)
'Zhicheng'	205.17 ± 5.17 a	21.61 ± 1.31 a	30.00 ± 2.18 a	29.44 ± 2.29 a	169.00 ± 20.84 ab	165.33 ± 6.33 bc
'Zhike'	142.33 ± 3.98 b	11.17 ± 1.20 c	8.49 ± 0.82 b	7.08 ± 0.63 c	115.67 ± 6.33 c	121.00 ± 15.95 c
'Hongju'	174.00 ± 30.44 ab	13.94 ± 1.69 bc	24.61 ± 3.41 ab	19.01 ± 1.33 b	156.67 ± 32.97 ab	127.33 ± 23.34 c
'Hongningmeng'	227.50 ± 24.52 a	24.39 ± 2.74 a	23.01 ± 1.61 ab	25.01 ± 2.69 a	182.00 ± 9.17 b	194.17 ± 2.42 ab
'Suanju'	222.67 ± 13.87 a	19.67 ± 3.79 ab	24.48 ± 2.01 ab	27.03 ± 1.45 a	248.33 ± 13.57 a	241.50 ± 16.86 a

Table 4 Effect of different rootstocks on the growth potential of 'Gonggan' trees cm

Rootstock	Plant height	Spring tip	Summer tip	Autumn tip	Crown diameter (east – west)	Crown diameter (south – north)
'Zhicheng'	137.33 ± 12.33 c	24.78 ± 2.47 ab	29.44 ± 4.00 a	37.78 ± 3.71 ab	102.00 ± 15.50 b	109.67 ± 3.84 b
'Zhike'	160.67 ± 10.17 c	27.00 ± 3.20 bc	25.33 ± 3.48 a	31.67 ± 4.38 b	108.67 ± 8.37 b	108.33 ± 13.30 b
'Hongju'	278.67 ± 8.51 a	18.11 ± 0.75 c	32.89 ± 1.57 a	19.89 ± 3.08 c	129.33 ± 4.98 ab	149.00 ± 2.52 a
'Hongningmeng'	204.67 ± 22.15 b	31.22 ± 5.76 a	31.22 ± 2.98 a	44.67 ± 4.90 a	105.67 ± 22.26 b	106.33 ± 14.84 b
'Suanju'	243.67 ± 22.98 ab	16.11 ± 0.99 c	27.89 ± 1.29 a	39.22 ± 1.21 a	156.00 ± 9.07 a	154.00 ± 25.42 a

3.3 Effect of different rootstock-scion combinations on the quality of citrus fruits

3.3.1 Effect of different rootstock-scion combinations on the appearance quality of citrus fruits. The key indicators influencing the appearance quality of fruits primarily include single fruit weight, fruit shape index, peel thickness, and edible rate. Notably, variations in the single fruit weight of 'Shatangju' were observed across different rootstocks. As illustrated in Tables 5 – 7, the single fruit weight of 'Shatangju' grafted onto the 'Suanju' rootstock was the highest, measuring 50.78 g. This weight was significantly greater than that of 'Shatangju' grafted onto the 'Zhike', 'Zhicheng', and 'Hongju' rootstocks. The fruits of 'Shatangju' grafted onto various rootstocks exhibited a highly oblate shape. Notably, the peel of 'Shatangju' grafted onto the 'Zhike' and 'Hongju' rootstocks was thicker, whereas the peel of those grafted onto the 'Zhicheng' and 'Suanju' rootstocks was comparatively thinner. The 'Chuntianju' variety grafted onto the 'Hongju' rootstock exhibited the highest single fruit weight, measuring 81.29 g. This weight was significantly greater than those grafted onto the other four rootstocks. Furthermore, the differences in single fruit weight among the 'Zhike', 'Hongju', 'Zhicheng', and 'Hongningmeng' rootstocks were not statistically significant. The fruits of 'Chuntianju' cultivated on various rootstocks exhibited an oblate shape, with peel thickness measurements ranging from 1.64 to 1.94 mm. No statistically significant differences were observed among the different rootstocks. The fruit shape index of 'Gonggan' cultivated on different rootstocks varied between 0.84 and 0.95, with the fruit exhibiting either a round or oval shape. The cultivar 'Suanju' produced the thickest peel, whereas 'Zhike' resulted in the thinnest peel.

Table 5 Effect of different rootstocks on the appearance quality of 'Shatangju' fruits

Rootstock	Weight//g	Transverse diameter//mm	Longitudinal diameter//mm	Fruit shape index	Peel thickness//mm
'Zhicheng'	38.25 ±2.73 b	42.25 ±1.36 a	34.24 ±1.11 a	0.81 a	1.90 ±0.17 a
'Zhike'	33.89 ±2.24 c	42.24 ±1.34 a	33.42 ±0.93 a	0.79 a	2.23 ±0.24 a
'Hongju'	43.26 ±2.05 b	45.08 ±0.88 a	34.92 ±0.63 a	0.77 a	2.37 ±0.24 a
'Suanju'	50.78 ±1.8 a	48.18 ±0.74 a	36.34 ±0.75 a	0.75 a	1.89 ±0.06 a

Table 6 Effect of different rootstocks on the appearance quality of 'Chuntianju' fruits

Rootstock	Weight//g	Transverse diameter//mm	Longitudinal diameter//mm	Fruit shape index	Peel thickness//mm
'Zhicheng'	76.33 ±7.18 ab	56.40 ±2.42 a	40.83 ±2.14 a	0.71 a	1.76 ±0.38 a
'Zhike'	68.45 ±12.94 b	54.19 ±3.97 a	39.17 ±2.36 a	0.72 a	1.74 ±0.48 a
'Hongju'	81.29 ±16.60 a	55.88 ±3.32 a	40.17 ±1.85 a	0.71 a	1.64 ±0.31 a
'Hongningmeng'	68.24 ±8.23 b	54.41 ±2.17 a	40.36 ±1.71 a	0.75 a	1.94 ±0.26 a
'Suanju'	65.92 ±9.56 b	52.72 ±2.93 a	39.34 ±3.22 a	0.72 a	1.77 ±0.30 a

Table 7 Effect of different rootstocks on the appearance quality of 'Gonggan' fruits

Rootstock	Weight//g	Transverse diameter//mm	Longitudinal diameter//mm	Fruit shape index	Peel thickness//mm
'Zhicheng'	145.35 ±6.55 a	66.06 ±1.37 a	62.00 ±1.44 a	0.94 ±0.01 a	2.08 ±0.09 a
'Zhike'	62.50 ±2.93 c	50.64 ±0.91 c	42.37 ±1.47 c	0.84 ±0.03 c	1.92 ±0.12 a
'Hongju'	112.42 ±4.95 b	56.48 ±1.40 b	53.59 ±1.34 b	0.95 ±0.01 a	2.14 ±0.09 a
'Suanju'	118.12 ±3.31 b	59.01 ±0.97 b	55.18 ±0.95 b	0.93 ±0.01 ab	2.31 ±0.10 a

3.3.2 Effect of different rootstock-scion combinations on the intrinsic quality of citrus fruits. As illustrated in Tables 8 – 10, there were notable variations in the soluble sugar, TSS, and TA of 'Shatangju' among various rootstocks. Specifically, the TSS content of 'Shatangju' cultivated on the 'Zhike' rootstock was significantly higher than that cultivated on the other rootstocks, categorizing it as a high TSS type. Additionally, the TA content of 'Shatangju' cultivated on different rootstocks ranged from 0.29% to 0.44%. The TA content of 'Shatangju' fruits cultivated on the 'Zhike' rootstock was the highest at 0.44%, while that cultivated on the 'Hongju' rootstock exhibited the lowest TA content at 0.29%. The soluble sugar content of 'Shatangju' fruits cultivated on different rootstocks varied between 7.99% and 11.84%, with 'Shatangju' fruits cultivated on 'Zhicheng' rootstock demonstrating a high soluble sugar content of 11.84%, in contrast to the lower content of 7.99% observed in the 'Hongju' rootstock. The edible rate of 'Shatangju' fruits ranged from 73% to 78%, and no significant differences were noted in the edible rates among various rootstocks. The TSS content of 'Chuntianju' fruits cultivated on various rootstocks revealed that the TSS content associated with 'Suanju' and 'Hongningmeng' rootstocks were significantly higher. Furthermore, the differences in TSS content among the 'Zhicheng', 'Zhike', and 'Hongningmeng' rootstocks were not statistically significant. In terms of TA, the fruits from the 'Suanju' rootstock exhibited the highest TA content, categorizing them as high-acid type fruits. The TA content of 'Chuntianju' fruits cultivated on the 'Hongningmeng' rootstock was marginally lower than those cultivated on the 'Suanju' rootstock, while the difference in TA content of 'Chuntianju' fruits between the 'Hongju' and 'Zhike' rootstocks was not statistically significant. The 'Chuntianju' fruits cultivated on 'Zhicheng' rootstock exhibited a lower TA content of 0.39%. The fruits derived from the 'Hongju', 'Zhike', and 'Hongningmeng' rootstocks were classified as medium-acid types. Furthermore, there was no significant difference in the edible rate of 'Chuntianju' fruits among the various rootstock-scion combinations. In the study of 'Gonggan' fruits cultivated on various rootstocks, it was observed that those grown on the 'Zhike' rootstock exhibited the highest soluble sugar content, whereas those cultivated on the 'Suanju' rootstock demonstrated the lowest soluble sugar content. The TSS content of 'Gonggan' fruits ranged from 9.8% to 10.5%, with no significant differences noted among different rootstocks. Furthermore, the solid-acid ratio of 'Gonggan' fruits derived from the 'Zhicheng' rootstock was significantly greater than those derived from the other three rootstocks. Additionally, there were no significant differences in the edible rate of 'Gonggan' fruits across various rootstock-scion combinations.

Table 8 Effect of different rootstocks on the intrinsic quality of 'Shatangju' fruits

Rootstock	Soluble sugar//%	TSS //%	TA //%	Solid-acid ratio	Edible rate//%
'Zhicheng'	11.84 ±0.13 a	13.83 ±0.05 b	0.34 ±0.003 c	40.67 a	78.00 a
'Zhike'	10.35 ±0.04 b	15.28 ±0.08 a	0.44 ±0.002 a	34.70 a	73.00 a
'Hongju'	7.99 ±0.10 d	11.80 ±0.09 c	0.29 ±0.001 d	40.69 a	76.00 a
'Suanju'	8.33 ±0.12 c	10.30 ±0.04 d	0.38 ±0.01 b	27.10 a	77.00 a

Table 9 Effect of different rootstocks on the intrinsic quality of 'Chuntianju' fruits

Rootstock	Soluble sugar // %	TSS // %	TA // %	Solid-acid ratio	Edible rate // %
'Zhicheng'	7.480 ± 0.614 bc	10.8 ± 0.8 c	0.39 ± 0.05 b	27.7 a	85.33 a
'Zhike'	7.877 ± 0.365 bc	11.0 ± 0.6 bc	0.45 ± 0.13 b	24.4 a	80.32 a
'Hongju'	7.838 ± 0.109 c	11.1 ± 0.5 bc	0.49 ± 0.06 b	22.7 a	84.46 a
'Hongningmeng'	8.261 ± 0.219 bc	11.4 ± 0.6 b	0.55 ± 0.03 b	20.7 b	82.3 a
'Suanju'	9.177 ± 0.471 a	12.7 ± 0.5 a	0.69 ± 0.03 a	18.4 b	83.07 a

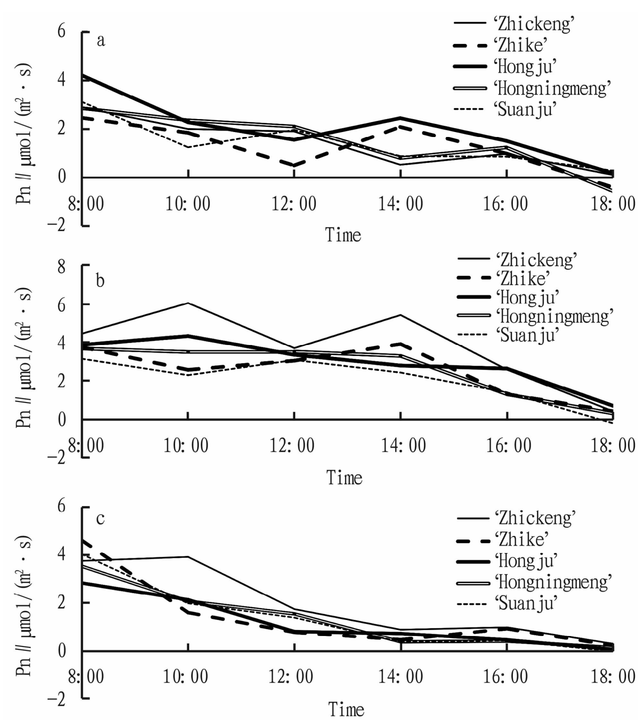
Table 10 Effect of different rootstocks on the intrinsic quality of 'Gonggan' fruits

Rootstock	Soluble sugar // %	TSS // %	TA // %	Solid-acid ratio	Edible rate // %
'Zhicheng'	11.63 ± 0.23 b	9.81 ± 0.16 a	0.28 ± 0.006 c	32.5 a	78 a
'Zhike'	12.56 ± 0.07 a	10.45 ± 0.13 a	0.47 ± 0.006 b	22.0 b	80 a
'Hongju'	9.89 ± 0.10 c	10.23 ± 0.16 a	0.49 ± 0.02 ab	20.8 b	77 a
'Suanju'	8.80 ± 0.06 d	10.50 ± 0.12 a	0.51 ± 0.005 a	20.6 b	82 a

3.4 Differential analysis of photosynthetic characteristics of citrus across different rootstock-scion combinations

3.4.1 Effect of various rootstock-scion combinations on daily Pn variations in citrus plants. Different rootstock-scion combinations exhibited varying photosynthetic characteristics in citrus plants, suggesting that the photosynthetic traits of these plants are intrinsically linked to both the rootstock and scion varieties. As illustrated in Fig. 1, the daily Pn variation of 'Shatangju' cultivated on various rootstocks exhibited a bimodal distribution. The initial peak occurred between 8:00 and 10:00 am, representing the maximum Pn for the entire day. The highest peaks were observed in the 'Hongju' rootstock, while the lowest peaks were recorded for the 'Suanju' rootstock. The peaks of the other three rootstocks exhibited minimal variation, falling within the range established by the 'Hongju' and 'Suanju' rootstocks. The initial peaks were consistently higher than the subsequent peaks. Specifically, the second peaks for the 'Zhicheng', 'Suanju', and 'Hongningmeng' rootstocks were observed at 12:00, while the second peaks for the 'Hongju' and 'Zhike' rootstocks were recorded at 14:00. All rootstock-scion combinations exhibited the phenomenon known as "midday depression of photosynthesis". The Pn of the 'Zhike' rootstock demonstrated the most significant change, decreasing by 1.87 μmol/(m^2 · s) over the same time period. In contrast, the 'Hongju' rootstock experienced a lesser decline, and the midday depression phenomenon was less pronounced compared to the other four rootstocks. From 14:00 onwards, the Pn of the 'Hongju' rootstock was observed to be higher than that of the other rootstocks. This finding suggests that the "midday depression of photosynthesis" of the plant exerted a relatively minor inhibitory effect on the Pn of the 'Hongju' rootstock. Consequently, the decline rate of Pn for the 'Hongju' rootstock was slower in comparison to the other four rootstocks. Furthermore, it was determined that the 'Hongju' rootstock exhibited the highest photosynthetic efficiency prior to 10:00 am.

The Pn of 'Chuntianju' cultivated on various rootstocks exhibited both "unimodal" and "bimodal" response curves. Specifically, the Pn associated with 'Suanju', 'Hongningmeng', and 'Zhike' rootstocks demonstrated an unimodal curve, with the highest peak for 'Suanju' occurring at 12:00, while the peaks for 'Hongningmeng' and 'Zhike' were observed at 14:00. In contrast, the 'Zhicheng' rootstock displayed a bimodal curve, with the first peak occurring at 10:00 and the second peak at 14:00, showing only a minor difference between the two peaks. Although the 'Hongju' rootstock also exhibited two peaks, the overall fluctuations in Pn were minimal. The phenomenon of midday depression of photosynthesis was most pronounced in the 'Zhicheng' rootstock, with its peak observed at 12:00. The daytime Pn of the 'Zhicheng' rootstock exhibited the greatest variability among the five rootstocks studied, surpassing that of the other four. This finding suggests that the leaves of the 'Zhicheng' rootstock demonstrated the highest efficiency in assimilating carbon dioxide (CO_2) and generating oxygen (O_2) per unit area, thereby highlighting its significant advantage in photosynthetic performance within the context of this experiment.



NOTE a. 'Shatangju'; b. 'Chuntianju'; c. 'Gonggan'.

Fig. 1 Effect of various rootstock-scion combinations on daily Pn variations in citrus plants

The daily variation curves of Pn in the rootstock-scion combinations of 'Gonggan' exhibited a unimodal pattern, with a peak value of 4.66 μmol/(m^2·s) observed between 8:00 and 10:00 am. Following this peak, Pn exhibited a continuous decline, and the midday depression of photosynthesis did not recover after this decrease. Furthermore, the maximum Pn value was highest in the 'Zhike' rootstock, with no significant differences noted among the other rootstocks.

3.4.2 Effect of various rootstock-scion combinations on photosynthetic characteristics of citrus. Tables 11 – 13 indicate that there were no significant differences in the Pn and Tr of 'Shatangju' among the five rootstocks measured throughout the day. However, significant differences in WUE were observed among various rootstocks, with the 'Hongju' rootstock exhibiting a significantly higher WUE compared to the other four rootstocks. Additionally, no significant differences were found between the 'Zhike' and 'Suanju' rootstocks. The 'Shatangju' cultivated on the 'Hongju' rootstock demonstrated optimal photosynthetic performance, while no significant differences in photosynthetic performance were noted among the other rootstocks.

Table 11 Comparison of photosynthesis in 'Shatangju' cultivated on various rootstocks

Rootstock	Pn//μmol/(m^2·s)	Tr//mmol/(m^2·s)	WUE//mmol/mol	AQY	CE
'Zhicheng'	3.77 a	1.56 a	2.40 b	0.013 7 a	0.014 4 a
'Zhike'	2.02 b	1.70 a	1.06 b	0.017 6 a	0.007 1 a
'Hongju'	2.94 ab	0.90 b	3.47 a	0.018 1 a	0.011 7 a
'Hongningmeng'	2.59 b	1.19 b	2.37 bc	0.086 6 a	0.010 3 a
'Suanju'	2.50 b	1.04 b	2.16 c	0.008 4 a	0.010 3 a

Table 12 Comparison of photosynthesis in 'Chuntianju' cultivated on various rootstocks

Rootstock	Pn//μmol/(m^2·s)	Tr//mmol/(m^2·s)	WUE//mmol/mol	AQY	CE
'Zhicheng'	1.38 b	0.94 b	1.70 b	0.008 5 a	0.006 8 a
'Zhike'	1.39 b	1.24 b	1.40 bc	0.017 5 a	0.005 6 a
'Hongju'	2.02 a	1.21 b	2.24 a	0.010 9 a	0.008 6 a
'Hongningmeng'	1.46 b	2.32 a	0.80 c	0.017 0 a	0.005 8 a
'Suanju'	1.24 b	1.19 b	1.24 bc	0.016 8 a	0.005 6 a

Table 13 Comparison of photosynthesis in 'Gonggan' cultivated on various rootstocks

Rootstock	Pn//μmol/(m^2·s)	Tr//mmol/(m^2·s)	WUE//mmol/mol	AQY	CE
'Zhicheng'	3.75 b	1.47 bc	2.55 a	0.008 9 a	0.012 9 a
'Zhike'	4.66 a	2.18 ab	2.07 b	0.011 3 a	0.017 9 a
'Hongju'	2.83 c	1.22 c	2.91 a	0.009 6 a	0.012 3 a
'Hongningmeng'	3.09 c	2.70 a	1.09 c	0.013 7 a	0.011 0 a
'Suanju'	4.02 a	2.77 a	1.42 c	0.017 1 a	0.014 6 a

The Pn of 'Chuntianju' cultivated on different rootstocks was found to be highest when using the 'Zhicheng' rootstock and lowest with the 'Suanju' rootstock. Additionally, the 'Zhike' rootstock exhibited a higher Tr. In terms of WUE, significant differences were observed among various rootstocks. Notably, the 'Hongju' rootstock demonstrated a WUE that was significantly greater than those of the other four rootstocks, while the 'Zhike' rootstock recorded the lowest WUE. The 'Zhicheng', 'Hongningmeng', and 'Suanju' rootstocks exhibited WUE values that fell between these two extremes. There were no significant differences observed in the AQY and CE of 'Chuntianju' when cultivated on various rootstocks. Notably, the overall photosynthetic performance of 'Chuntianju' was found to be optimal when grown on the 'Zhicheng' rootstock. The capacity of plants to utilize low light conditions and convert absorbed light energy into proteins is indicated by the AQY value. There was no statistically significant difference in the AQY of 'Shatangju' leaves cultivated on five different rootstocks. The magnitude of the CE values indicated that various rootstock-scion combinations did not exhibit significant differences in their efficiency of CO_2 assimilation. Furthermore, the differences in CO_2 assimilation efficiency among the rootstocks were relatively minor, with only the 'Zhicheng' rootstock demonstrating a comparatively high assimilation efficiency.

A significant variation in Pn was observed in 'Gonggan' among the five rootstocks, ranked from highest to lowest as follows: 'Zhike' rootstock, 'Suanju' rootstock, 'Zhicheng' rootstock, 'Hongningmeng' rootstock, and 'Hongju' rootstock. The maximum Pn value recorded was 4.60 μmol/(m^2·s), while the minimum was 2.83 μmol/(m^2·s). The highest Tr was associated with the 'Suanju' rootstock, whereas the lowest Tr was noted in the 'Hongju' rootstock. Regarding WUE, the 'Hongju' rootstock exhibited the highest value, in contrast to the 'Hongningmeng' rootstock, which demonstrated the lowest. Overall, the 'Zhike' rootstock exhibited the most favorable photosynthetic performance.

3.4.3 Effects of different rootstock-scion combinations on photosynthetic physiological and ecological indicators of citrus. As illustrated in Tables 14 – 16, there was no significant difference in soluble protein content among the 'Shatangju' cultivars grown on different rootstocks, with the 'Zhike' rootstock exhibiting a relatively higher content, while the 'Zhicheng' rootstock demonstrated the lowest levels. In contrast, significant variations in specific leaf weight were observed among the five rootstocks, with the 'Zhicheng' rootstock yielding the highest specific leaf weight. Regarding chlorophyll and carotenoid content, the 'Zhicheng' rootstock also recorded the highest values. However, the 'Zhike' rootstock outperformed the others across all measured parameters, with the levels of various photosynthetic pigments significantly exceeding those of the other four rootstocks. The 'Chuntianju' cultivar exhibited no significant variation in soluble protein levels across different rootstocks. However, notable differences were observed in specific leaf weight, chlorophyll content, and carotenoid levels. The 'Zhike' rootstock demonstrated superior performance in terms of soluble proteins, chlorophyll, and carotenoids, while the 'Hongningmeng' rootstock displayed comparatively lower values for each of these indicators. There were no significant differences observed in the soluble protein content and specific leaf weight of the 'Gonggan' cultivar across various rootstocks. Regarding photosynthetic pigments, the chlorophyll a content among the five rootstocks ranged from 1.83 to 2.52 mg/g, while the chlorophyll b content varied from 0.68 to 0.98 mg/g. Notably, the 'Hongju' rootstock exhibited the highest chlorophyll a + b value, whereas the 'Zhike' rootstock demonstrated a superior chlorophyll a/b ratio. In terms of carotenoid content, the 'Hongju' rootstock also displayed the highest level, with minimal variation observed among the other four rootstocks.

Table 14 Effect of different rootstocks on soluble protein, specific leaf weight and photosynthetic pigments of 'Shatangju' leaves

Rootstock	Soluble protein mg/g	Specific leaf weight // mg/cm²	Chlorophyll				Carotenoid mg/g
			a // mg/g	b // mg/g	a + b // mg/g	a/b	
'Zhicheng'	2.57 ± 0.02 a	10.71 ± 0.32 a	2.35 ± 0.02 a	1.12 ± 0.05 a	3.47 ± 0.07 a	2.12 ± 0.08 c	0.54 ± 0.02 a
'Zhike'	2.93 ± 0.02 a	8.98 ± 0.25 c	2.05 ± 0.02 b	0.86 ± 0.01 b	2.91 ± 0.03 b	2.39 ± 0.02 b	0.48 ± 0.01 ab
'Hongju'	2.69 ± 0.01 a	9.40 ± 0.27 bc	1.82 ± 0.04 c	0.75 ± 0.01 c	2.57 ± 0.05 c	2.44 ± 0.02 a	0.45 ± 0.01 b
'Hongningmeng'	2.74 ± 0.02 a	10.23 ± 0.3 ab	1.87 ± 0.07 b	0.76 ± 0.04 bc	2.63 ± 0.11 b	2.47 ± 0.04 a	0.42 ± 0.02 bc
'Suanju'	2.88 ± 0.02 a	10.85 ± 0.34 a	1.75 ± 0.01 c	0.73 ± 0.02c	2.47 ± 0.02 c	2.41 ± 0.05 ab	0.40 ± 0.00 c

Table 15 Effect of different rootstocks on soluble protein, specific leaf weight and photosynthetic pigments of 'Chuntianju' leaves

Rootstock	Soluble protein mg/g	Specific leaf weight mg/cm²	Chlorophyll				Carotenoid mg/g
			a // mg/g	b // mg/g	a + b // mg/g	a/b	
'Zhicheng'	2.66 ± 0.02 a	9.4 ± 0.17 b	1.91 ± 0.02 b	0.92 ± 0.04 ab	2.83 ± 0.06 bc	2.10 ± 0.08 c	0.44 ± 0.02 bc
'Zhike'	2.76 ± 0.02 a	9.16 ± 0.46 bc	2.60 ± 0.03 a	1.05 ± 0.03a	3.65 ± 0.06a	2.47 ± 0.03 b	0.55 ± 0.00 a
'Hongju'	2.80 ± 0.02 a	9.39 ± 0.21 b	1.99 ± 0.05 b	0.82 ± 0.02b	2.81 ± 0.07bc	2.43 ± 0.02 b	0.46 ± 0.01 b
'Hongningmeng'	2.73 ± 0.02 a	8.0 ± 0.20 c	1.86 ± 0.10 bc	0.75 ± 0.05bc	2.62 ± 0.15c	2.49 ± 0.06 b	0.42 ± 0.02 c
'Suanju'	2.89 ± 0.02 a	10.78 ± 0.28 a	1.94 ± 0.02b	0.70 ± 0.01c	2.64 ± 0.03bc	2.78 ± 0.02 a	0.45 ± 0.01 b

Table 16 Effect of different rootstocks on soluble protein, specific leaf weight and photosynthetic pigments of 'Gonggan' leaves

Rootstock	Soluble protein mg/g	Specific leaf weight // mg/cm²	Chlorophyll				Carotenoid mg/g
			a // mg/g	b // mg/g	a + b // mg/g	a/b	
'Zhicheng'	2.77 ± 0.01 a	8.54 ± 0.21 a	2.24 ± 0.08 b	0.84 ± 0.02 b	3.08 ± 0.10 b	2.68 ± 0.03 b	0.52 ± 0.02 a
'Zhike'	2.84 ± 0.01 a	9.76 ± 0.27 a	2.01 ± 0.06 c	0.71 ± 0.02 c	2.72 ± 0.08 c	2.85 ± 0.03 a	0.51 ± 0.01 a
'Hongju'	2.75 ± 0.02 a	8.53 ± 0.29 a	2.52 ± 0.05 a	0.98 ± 0.02 a	3.50 ± 0.07 a	2.56 ± 0.01 b	0.53 ± 0.02 a
'Hongningmeng'	2.65 ± 0.02 a	9.14 ± 0.44 a	1.83 ± 0.01 d	0.68 ± 0.03 c	2.51 ± 0.04 c	2.70 ± 0.10 b	0.36 ± 0.01 b
'Suanju'	2.70 ± 0.02 a	9.06 ± 0.26 a	2.27 ± 0.04 b	0.86 ± 0.02 b	3.13 ± 0.06 b	2.64 ± 0.04 b	0.49 ± 0.01 a

4 Discussion and conclusions

4.1 Discussion Rootstocks serve as the foundation for grafted fruit trees and significantly affect the size, growth, development, and fruit quality of the scion varieties[11]. Shen Lijuan *et al.* [12] demonstrated that various rootstocks grafted with 'Xinhuicheng' exhibited inconsistent performance. Specifically, 'Xinhuicheng' cultivated on trifoliate orange rootstock displayed a small crown and limited growth potential, whereas 'Xinhuicheng' grafted onto 'Suanju' rootstock showed rapid crown formation and vigorous plant growth. Chun Changpin *et al.* [13] conducted a study examining the intrinsic and appearance quality of 'Jincheng' fruits across 11 different rootstocks. The findings indicated that 'Jincheng' fruits exhibited variations in peel brightness, soluble solids content, and edible rate depending on the rootstock utilized. Liu Yaoxin *et al.* [14] conducted a study on the effects of the 'Zhicheng' rootstock on the growth and fruit quality of 'Wogan' trees in the Wuming District of Nanning City, Guangxi Province. The findings indicated that 'Wogan' trees grafted onto the 'Zhicheng' rootstock exhibited superior overall performance in the southeastern region of Guangxi. Consequently, the 'Zhicheng' rootstock is deemed suitable for cultivating 'Wogan' in this area. Xu Zhilong *et al.* [15] conducted a comparative analysis of kumquat (*Fortunella margarita*) grafted onto various rootstocks, specifically kumquat seedling trees, sour tangerine, and trifoliate orange, with respect to tree growth and fruit quality. The findings indicated significant differences in the performance of kumquats depending on the rootstock utilized, with sour tangerine emerging as the most effective rootstock for Yangshuo kumquat. Wang Rong *et al.* [16] discovered that the 'Zhicheng' rootstock exhibited a higher soluble solids content in Wenzhou tangerine varieties, specifically 'Guoqing No. 1' satsuma and 'Huanong Bendizao' tangerine.

This study, conducted in the red loam soil of the Zhaoqing area, demonstrated that trees cultivated on 'Hongju' and 'Suanju' rootstocks exhibited generally more vigorous growth potential, characterized by larger crowns and enhanced tree vigor. In contrast, trees grown on 'Zhicheng' and 'Hongningmeng' rootstocks displayed moderate growth potential, while those on 'Zhike' rootstock were notably smaller, leading to a more dwarfed stature. The TSS and TA contents were found to be elevated in 'Shatangju' grafted onto 'Zhike' rootstock, 'Chuntianju' grafted onto 'Suanju' rootstock, and 'Gonggan' grafted onto 'Suanju' rootstock.

The material basis for plant growth and development is derived from photosynthesis, which is influenced to varying extents by a range of physiological and ecological factors, including temperature, humidity, and light intensity[17]. The photosynthetic capacity of a plant is directly indicated by its Pn value, which serves as a measure of the material and energy transformations occurring between the plant and its external environment[18]. The daily fluctuations in photosynthesis among citrus varieties predominantly exhibit unimodal, bimodal, and multimodal patterns[17]. In this study, the daily variation in Pn for each rootstock-scion combination displayed "unimodal, and bimodal" curves, characterized by the occurrence of midday depression of photosynthesis. The 'Shatangju' cultivar, when grown on various rootstocks, consistently exhibited bimodal distribution curves. In contrast, the 'Chuntianju' cultivar displayed both unimodal and bimodal curves across different rootstocks. Additionally, the 'Gonggan' cultivar, regardless of the rootstock utilized, demonstrated unimodal curves exclusively. The phenomenon of midday depression of photosynthesis typically occurs at noon, around 12:00, when the Tr of citrus leaves reaches its peak for the day, coinciding with elevated atmospheric temperatures. The phenomenon of midday depression of photosynthesis observed in citrus plants may be attributed to the accelerated evaporation of water resulting from a rapid increase in temperature within the protective nets. This temperature rise decreases the relative humidity inside the nets, which in turn can lead to the closure of certain stomata and the subsequent inhibition of photosynthesis[19]. Consequently, when faced with hot and dry weather conditions during production, midday depression of photosynthesis may occur. It is advisable to employ methods such as spray irrigation on the leaf surface and the use of shade nets to enhance the ambient temperature. These strategies aim to mitigate the adverse effects associated with the inhibition of midday depression of photosynthesis[20].

4.2 Conclusions This study examined 15 citrus rootstock-scion combinations in relation to the distinctive soil properties of red loam in the Zhaoqing region. The findings indicated notable variations in phenological periods, tree growth potential, fruit quality, and photosynthetic characteristics among different citrus rootstock-scion combinations. The comprehensive evaluation indicates that, in the context of the red loam soil found in the Zhaoqing area, the rootstocks deemed suitable for the cultivation of 'Shatangju' are 'Zhike' and 'Hongju'. For 'Chuntianju', the appropriate rootstocks include 'Zhike', 'Zhicheng', and 'Hongju'. Additionally, the rootstocks suitable for 'Gonggan' are 'Zhike' and 'Suanju'.

References

[1] YIN HL, LIU HY. Distribution characteristics of citrus varieties and selection of varieties suitable for planting in China[J]. China Fruits, 2022, 64(1): 1-7. (in Chinese).

[2] JIANG H, QIU XF, YANG FM, et al. Survey on the basic situation of orange orchards in Xijiang River Basin of Guangdong and thoughts on development[J]. Southern Horticulture, 2024, 35(3): 7-14. (in Chinese).

[3] ZHU SP, CHEN J, MA YY, et al. Advances in the studies on citrus rootstock evaluation and application[J]. Acta Horticulturae Sinica, 2013, 40(9): 1669-1678. (in Chinese).

[4] LIU YX, CHEN DK, LI GG, et al. Effect of different rootstocks on Orah's tree body and fruit quality[J]. Journal of Southern Agriculture, 2019, 50(2): 338-343. (in Chinese).

[5] GONG LJ. A primer on citrus rootstock selection for 'Asumi' mandarin[J]. Sichuan Agricultural Science and Technology, 2021(2): 15-16, 19. (in Chinese).

[6] FAN SL, WU BB, LI HM, et al. Early growing performance of 'Ehime Kashi No. 28' mandarin grafted on different rootstocks and interstocks[J]. South China Fruits, 2021, 50(3): 32-35. (in Chinese).

[7] PENG Y, MA XY, FENG TL, et al. Selection of excellent rootstocks for Shatang mandarin based on combined analysis of plant height, yield, and quality[J]. Journal of Fruit Science, 2024, 41(6): 1078-1093. (in Chinese).

[8] CAI YX, ZHANG BF, LIAO GX, et al. A preliminary study on the differences in cultivation traits of 'Ehime Kashi No. 28' mandarin on three different rootstocks in Yidu[J]. South China Fruits, 2020, 49(3): 21-22. (in Chinese).

[9] LIU Z, HONG LW, LI J, et al. Effects of different rootstocks on fruit quality of 'Shatangju' mandarin[J]. Guangdong Agricultural Sciences, 2016, 43(8): 39-44. (in Chinese).

[10] WU Y. Study on seedling growth and drought resistance of different Citrus cultivars grafted on 'Pujiang Xiangcheng'[D]. Chengdu: Sichuan Agricultural University, 2022. (in Chinese).

[11] ZHU SP, CHEN CW, LIU ZJ, et al. Investigation and comparison of the performance of Carrizo Citrange in China[J]. South China Fruits, 2020, 49(3): 1-8. (in Chinese).

[12] SHEN LJ, SHI JQ. Effects of intermediate rootstocks on growth, fruiting and quality of Xinhui oranges[J]. Journal of Fruit Science, 1993(1): 29-32. (in Chinese).

[13] CHUN CP, PENG LZ, LEI T, et al. Effects of rootstocks on fruit quality of 'Jincheng' sweet orange[J]. Acta Horticulturae Sinica, 2010, 37(6): 991-996. (in Chinese).

[14] LIU YX, QIU HJ, OU ZT, et al. Comprehensive performance of Orah grafted on Carrizo Citrange rootstock in southern area of Guangxi[J]. Journal of Southern Agriculture, 2023, 54(1): 209-216. (in Chinese).

[15] XU ZL, SU SY, YIN HL. Effects of different rootstocks on tree growth and fruit quality of kumquat[J]. Journal of Huazhong Agricultural University, 2014, 33(5): 32-35. (in Chinese).

[16] WANG R, ZHANG LY, TAN FQ, et al. Effects of five rootstocks on plant growth and fruit quality of 'Guoqing No. 1' satsuma and 'Huanong Bendizao' tangerine[J]. South China Fruits, 2019, 48(6): 12-16. (in Chinese).

[17] MEI ZM, LUO SX, YIN HL, et al. Effects of different rootstocks on growth and photosynthetic characteristics of young Guiqi 1 navel orange trees[J]. Journal of Southern Agriculture, 2014, 45(3): 434-441. (in Chinese).

[18] SONG QF, OUYANG B. Daily variation of photosynthetic physio-ecological characteristics of different citrus cultivars[J]. Guizhou Agricultural Sciences, 2009, 37(9): 178-181. (in Chinese).

[19] LIAO L, CAO SY, RONG Y, et al. Effects of different rootstocks on photosynthetic characteristics, activities and gene expression of key enzymes of photosynthesis in Huangguogan[J]. Acta Agriculturae Zhejiangensis, 2016, 28(5): 769-775. (in Chinese).

[20] XU DQ. Ecology, physiology and biochemistry of midday depression of photosynthesis[J]. Plant Physiology Communications, 1990(6): 5-10. (in Chinese).