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Original Research

Growth and Physiological Responses of Six Species of Crassulaceae in Green Roof to Consecutive Water Deficit Conditions

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Abstract

At present, the plant species used for green roof are limited. In order to further expand the plant species used for green roof, it is particularly important to explore the adaptability of different plant species. In this study, 6 species of Crassulaceae (*Kalanchoe blossfeldiana* (*K. blossfeldiana*), *Sedum lineare* (*S. lineare*), *Hylotelephium erythrostictum* (*H. erythrostictum*), *Phedimus aizoon* (*P. aizoon*), *Rhodiola rosea* (*R. rosea*) and *Sedum sarmentosum* (*S. sarmentosum*)) were selected and planted on the stainless-steel planting rack on the roof with a substrate thickness of 15 cm. After normal maintenance and management for 1-month, continuous water deficit treatment was carried out. The physiological properties were measured at 0, 10, 20, 30 and 40 days, respectively. The results showed that: (1) The 6 species of Crassulaceae grew normally and well within 0-20 days. At 30 days, *K. blossfeldiana* had the most severe wilting rate (53%) and *S. lineare* had the least wilting rate (14%), but still maintained basic ornamental value. After 40 days of water deficit treatment, all the plants lost their ornamental value. (2) Among the 6 species under different water deficit treatment times, *S. lineare* and *P. aizoon* ranked between 1-3 in the 0-20 days when the water deficit degree was mild, and still ranked first and second in the 30-40 days when the water deficit was severe, with the best performance throughout the whole process, which could adapt to extensive green roof and did not need too much management. *S. sarmentosum* and *K. blossfeldiana* ranked 4-6 in the membership function under 40-day water deficit stress, with the worst performance. They are not suitable for extensive green roof and need careful management. In addition, considering the ornamental effect and ecological benefits of green roof, except *K. blossfeldiana* and *S. sarmentosum*, the other four plant species are suitable for the application of extensive green roof.

Keywords: green roof, persistent water deficit, growth, physiological properties, Crassulaceae

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Introduction

In the process of rapid urbanization, many significant achievements have been made in urban construction [1], but a series of urban problems have also emerged, among which ecological deterioration and environmental destruction are the most typical ones [2]. In recent years, ecological protection has received unprecedented attention, green is becoming the direction of the general trend [3]. As an important content of ecological civilization construction in China, urban greening has been paid more and more attention [4,5]. On the other hand, with the growing need for a better life, people begin to pay more and more attention to the restoration of ecological environment and the improvement of living environment [6]. With the acceleration of urbanization and the increase of population, the per capita urban green space is becoming smaller and smaller [7]. In this era, it is not realistic to increase the green area in the limited urban space only by expanding the urban green space [8,9]. In high-density cities, the urban ground green space decreases, which promotes the extension of greening to three-dimensional space [10]. Green roof has become one of the effective measures to increase the urban green coverage rate and alleviate urban energy and ecological environment problems [11,12].

Green roofs add many ecological benefits to the city, including stormwater management [13], energy conservation [14], mitigation of urban heat island effects [15], noise and air pollution reduction [16], carbon sequestration [17], and increasing biodiversity [18], etc. Under the special condition of green roof, plants are planted isolated from the ground and lack of underground water supply [19]. At the same time, the light is strong, the summer temperature is high, the wind speed is high, and the water evaporation is fast [20]. Therefore, the water deficit resistance of green roof plants is extremely high. Crassulaceae is known for its strong growth, short plants, dense branches and leaves, long green period, strong stress resistance, wide suitable range, extensive management and other advantages in urban landscape greening [21, 22]. So, it has been gradually promoted and applied, especially in the green roof, three-dimensional greening and other harsh living environment [23]. Based on these traits, it has an irreplaceable position. As commonly used plants in green roof, research on the drought resistance and comparative screening of *Sedum* is of great significance for the application of green roof and increasing the ecological benefits of green roof [24].

Crassulaceae has good adaptability to the harsh conditions of green roof [25]. Oztan and Arslan studied the drought resistance of different short evergreen succulent plantlets prone to flatness. By observing external morphology and carrying out physiological tests, 27 species of *Sedum*, *Silene*, *Euphorbia* and *Sempervivum* were screened out [26]. 11 species of *Sedum* and a variety of plants of *Sempervivum* were selected with the condition of the cold and drought resistance under the thin soil layer. The growth of 18 native tree species and 9 species of Crassulaceae in the roof simulator during the winter were investigated by measuring chlorophyll fluorescence and related physiological indicators. It found that all Crassulaceae plants survived the winter and grew well. Among them, 4 plant species can adapt to extensive green roof without irrigation in Michigan [27]. Li screened plants suitable for green roof in Fuzhou, China through physiological indexes and proved that *Rhodiola rosea*, *Sedum lineare* and *Sedum sarmentosum* have strong resistance to high temperature [28]. *Sedum alfredii*, *Brunfelsia latifolia*, and *Gardenia jasminoides* Ellis var. *grandiflora* have weak heat tolerance.

Green roof is one of the important ways to increase urban green area and improve the ecological environment [29, 30]. The selection of plant species directly determines the management cost, popularization degree and ecological benefits of green roof [31]. As a common plant used in green roof, the Crassulaceae has been the focus of attention [32]. Previous studies have studied the growth status and stress resistance of some Crassulaceae plants in some areas under different conditions [33], but the effects of continuous water deficit on Crassulaceae plants for green roof have not been reported. Prior to this study, the other research work was carried out at the same site and the related results have been published. Interestingly, after the experiment was over, we found that the Crassulaceae plants that were left over from the experiment performed the best over the long term. Therefore, in this study, to more fully verify the performance of Crassulaceae, we added species of Crassulaceae, 6 species of Crassulaceae commonly used in green roof were selected and subjected to continuous water deficit treatment for 40 days. The growth and physiological parameters were analyzed to provide scientific and reasonable reference for the selection of green roof plants. By comparing the performance of six species of Crassulaceae on green roofs, it is expected to select suitable plants for application. Finally, we hope to improve the urban ecological environment and promote the sustainable development of city.

Materials and Methods

Overview of the Experimental Area

The experiment was conducted from March 11, 2022 to May 29, 2022. The experiment was conducted on the roof of the Architecture and Art Office Buildings of Shandong Jianzhu University in Licheng District, Jinan City, China and in the laboratory of Cavens Testing Institution in Nanjing City, China.

Jinan (36°02‘~37°54’N and 116°21’~117°93’E) is located in the central region of Shandong Province, China. The total area is 10244.45 km^2. It is in the warm temperate zone of the continental monsoon, and there is plenty of rain and light.

Weather Overview

From April 19, 2022 to May 28, 2022, the daily maximum and minimum temperature and daily relative humidity within the 40-day water deficit treatment in Licheng District, Jinan City, Shandong Province, China are shown in Fig. 1a) and b), respectively. The data was obtained by software WheatA. The average of maximum daily temperature was 22.63ºC, the average of minimum daily temperature was 13.32ºC, and the average temperature was 18.02ºC. The average relative humidity was 56.25%. Rainfall was excluded due to water deficit treatment.

Experimental Methods

In previous experiments, we found that some Crassulaceae plants that were left over from the experiment performed the best over the long term. Then we selected six species of Crassulaceae which was performed well for the experiment. They were *Kalanchoe blossfeldiana* (*K. blossfeldiana*), *Sedum lineare* (*S. lineare*), *Hylotelephium erythrostictum* (*H. erythrostictum*), *Phedimus aizoon* (*P. aizoon*), *Rhodiola rosea* (*R. rosea*) and *Sedum sarmentosum* (*S. sarmentosum*). A total of six groups, were planted on a 60*60*20 cm stainless steel planting shelf on the roof of the Jianyi Hall of Shandong Jianzhu University. Among them, treatment and control were set up in each group. Using 15 cm thick substrate, perlite: vermiculite: turfy soil = 1:1:1, as shown in Fig. 2. These plants were watered once every two days, 10 liters each time, and lasting for a month. Water deficit treatment was carried out after that management. Accordingly, the control group of each plant species was managed normally. Furthermore, canopy (Polyethylene PE rain-proof cloth suspended by a rope) was built in rainy days to ensure water deficit conditions. Malondialdehyde (MDA), catalase (CAT), peroxidase (POD), and superoxide dismutase (SOD) of each plant were measured at 0, 10, 20, 30 and 40 days respectively, and biological replicates of each index were performed three times. For the determination of each index, 2 g fresh leaf samples were taken, flash-frozen with liquid nitrogen after removing large leaf veins, and put into ziplock bags of different types, which were kept fresh on dry ice and sent to Nanjing Cavence Testing Technology Co., LTD. The indexes of MDA, CAT, POD and SOD were measured with the kit of Nanjing Mufan Biotechnology Co., LTD. The relative chlorophyll content (RCC) was measured with RN-YL01 handheld chlorophyll meter.

The experimental principle of index determination is as follows:

CAT can decompose H_2O_2, which is quickly terminated by adding excessive ammonium molybdate. The remaining H_2O_2 reacts with ammonium molybdate to form a light-yellow complex. The activity of CAT can be calculated by measuring its change at 405 nm.

Under the catalysis of POD, hydrogen peroxide oxidizes guaiacol to a brown substance, which has the maximum light absorption at 470 nm, so the activity of peroxidase can be measured by the change of absorbance at 470 nm.

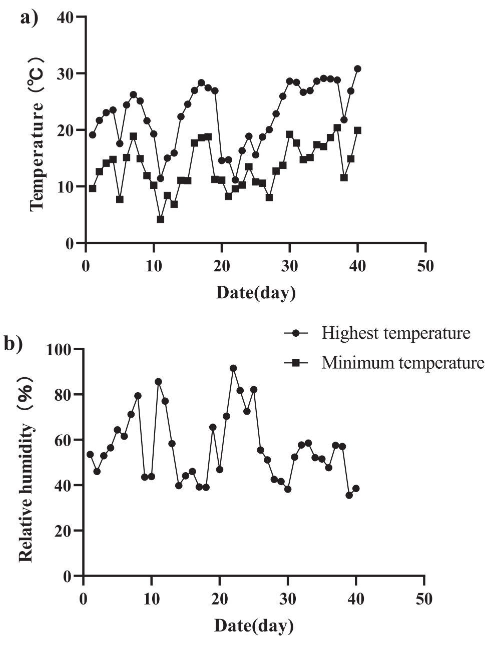

Fig. 1. Weather conditions in Licheng District of Jinan City during the experiment. a) the daily maximum and minimum temperature, and b) the relative humidity.

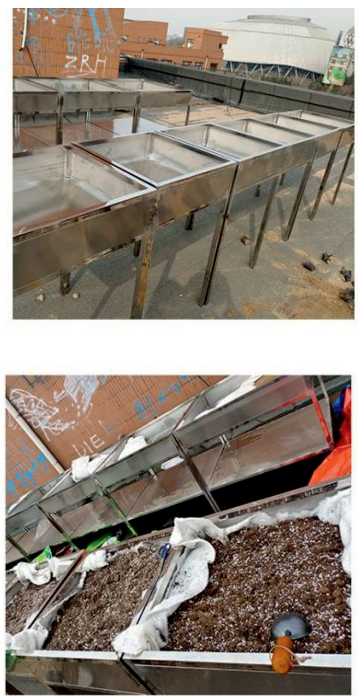

Fig. 2. The experiment setup and site.

The reaction system of xanthine and xanthine oxidase was used to generate superoxide anion ($O_2^{\cdot-}$), and the superoxide anion reducible azolium tetrazolium was used to form blue methyl, which was absorbed at 560 nm. Superoxide anion can be removed by SOD, so as to inhibit the formation of methyl black. The deeper the blue of the reaction solution, the lower the SOD activity, and the higher the activity.

Under acidic and high temperature conditions, MDA can react with thiobarbituric acid (TBA) to produce red-brown products with a maximum absorption wavelength of 532 nm. In addition, the maximum absorption wavelength of sucrose and TBA color reaction products in plant tissues is 450 nm, but there is also absorption at 532 nm. This interference should be removed during measurement. Thus, the content of malondialdehyde in the sample can be accurately calculated.

Statistical Analysis

SPSS Statistics 26.0 and Microsoft Excel 2010 were used for statistical analysis. One-way analysis of variance and Duncan's multiple comparison method were used for data analysis with $P \le 0.05$. As there was almost no significant difference in the control group of each plant species itself during the experiment. Therefore, the value on 0 day was taken as reference for the control group. In addition, GraphPad Prism 9.4.1 was used to draw the charts.

The determined indexes were calculated by fuzzy mathematics subordinate function value method (SFV) or anti-subordinate function value method (ASFV) for comprehensive evaluation at each time point under different water deficit treatment time conditions according to the method of Li et al [34]. The subordinate function value is calculated as follows:

$$X(\mu) = \frac{X - X_{\min}}{X_{\max} - X_{\min}}$$
$$\Delta = \sum X(\mu)/n \qquad (1)$$

$$X(\mu) = 1 - \frac{X - X_{\min}}{X_{\max} - X_{\min}}$$
$$\Delta = \sum X(\mu)/n \qquad (2)$$

Results and Discussion

Effects of Continuous Water Deficit on the Growth States of Six Plants

After water deficit treatment, the growth status of plants in each treatment period was photographed and recorded (as shown in Fig. 3). On the 10th and 20th day, all six plant species grew well, and on the 10th day the growth was better than that on the 0 day. *K. blossfeldiana* had fully blossomed on the 10th day, and the density of growth of other plants was obviously better than that on the 0th day. On the 30th day, wilting appeared in different degrees in each plant, *K. blossfeldiana*'s flowers and leaves partially withered. The color of *S. lineare* changed from green to yellow. The leaves of *H. erythrostictum*, *P. aizoon*, *R. rosea* and *S. sarmentosum* were partly dehydrated and withered, but those changes did not affect the overall viewing.

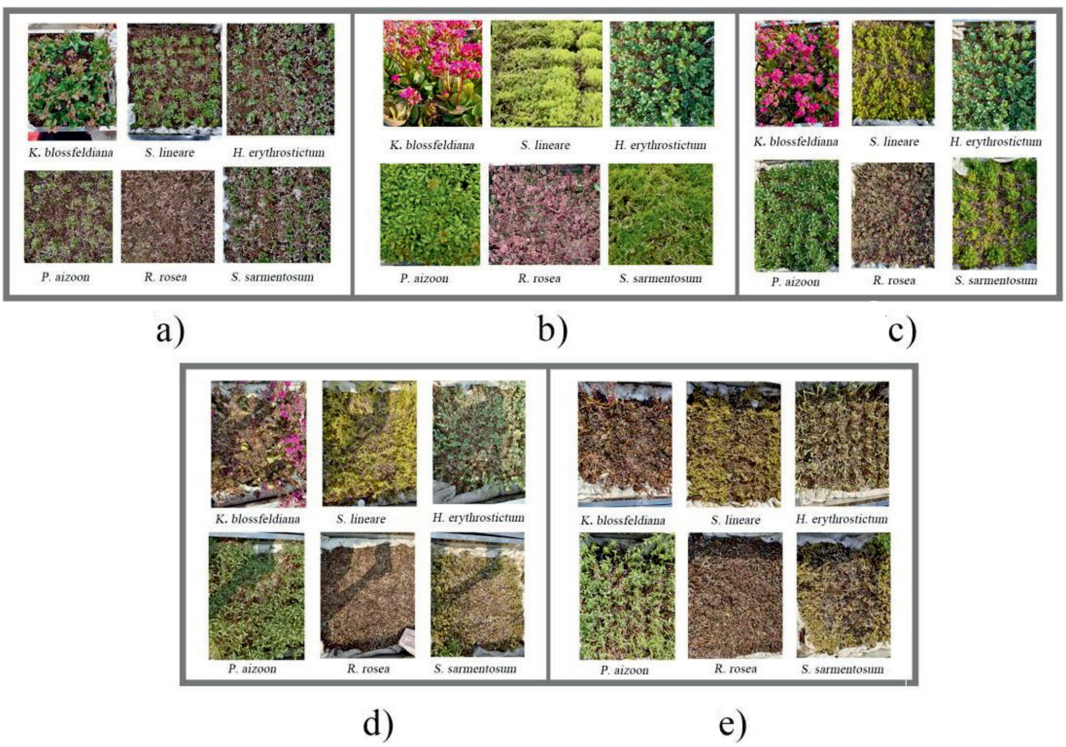

Fig. 3. Growth state of plants. a), b), c), d) and e) show the growth state of six plant species at 0, 10, 20, 30 and 40 days, respectively.

On the 40th day, all the plant species were almost severely wilted and lost their ornamental and ecological value.

The growth of plant species was observed, and the wilting rate of each plant in different periods was recorded (as shown in Table 1). No plants appeared wilting state from day 0 to day 10. On the 20th day, *K. blossfeldiana* showed mild wilting, with a wilting rate of 10%. On the 30th day, *K. blossfeldiana* had the most severe wilting rate (53%) and *S. lineare* had the least wilting rate (about 14%). On day 40, *K. blossfeldiana* had the most severe wilting rate with 90%, and *P. aizoon* had the least wilting rate with 49%.

Green roof plays a direct role in improving urban ecological environment and is a bridge between buildings and natural ecological environment [35]. As an indispensable part of green roof, plants' stress resistance is an important condition for whether they can be selected as green roof plants [36]. At present, most of the green roof in Jinan, China is extensive, lacking in management and relying on natural rainfall irrigation. In this respect, drought resistance of plants is necessary. Therefore, effects of prolonged water deficit stress on six species of Crassulaceae in green roof were discussed and compared in this study.

In order to explore the growth status of Crassulaceae plants under drought stress, the growth of Crassulaceae plants under several substrate thicknesses was investigated [37]. The results show that irrigation must be carried out at least every 14 days when the substrate thickness is 2 cm. When the substrate thickness is 6 cm, it should be irrigated at least once every 28 days. When the substrate thickness was 10 cm, the experimental plants could still grow normally without watering for up to 88 d. In this experiment, the conditions for growing plants were observed after each time period of water deficit treatment, and we found that plant growth status could be evident in normal. All plant species grew well on 0-20 days. However, plants appeared different degree of wilting on 30 days, but they could still maintain the basic ornamental value and ecological value. As the water deficit continued to increase, when up to the 40th day, all the plants basically lost their ornamental value and showed severely wilting. Compared with Vanwoert's research results, the normal growth time of plants under water deficit stress was relatively short, which may be caused by differences in temperature, humidity, latitude and the selection of Crassulaceae plants between the two studies.

Effects of Continuous Water Deficit on Physiological Characters of Six Plant Species

Under water deficit stress, MDA content of each plant at different time points showed significant differences ($P \leq 0.05$). According to Fig. 4a), with the increase of water deficit time, MDA contents in *K. blossfeldiana*, *H. erythrostictum*, *S. lineare*, *P. aizoon* and *S. sarmentosum* decreased first and then increased, and *R. rosea* showed an increasing trend on the 10th day. Compared with the MDA content of the six plants on day 0 and day 40, the MDA content of *R. rosea* increased the most, which was 56.19 nmol g^{-1} fresh weight, and *P. aizoon* showed the minimum increase with 0.66 nmol g^{-1} fresh weight.

Under treatment condition, POD activity of each plant was significantly different at different time points except *P. aizoon* ($P \leq 0.05$). However, there is no significant difference in POD activity of *P. aizoon*. According to Fig. 4b), with the increase of water deficit time, POD activities of *K. blossfeldiana*, *H. erythrostictum*, *S. lineare* at different time points decreased first and then increased. Among them, *K. blossfeldiana*, *S. lineare* declined on day 10, but *H. erythrostictum* decreased on day 20. In addition, POD activity of *R. rosea* and *S. sarmentosum* has been on the rise. The POD activity of the six species on day 0 was compared with that on day 40, except no significant difference in *P. aizoon*, POD activity of *R. rosea* increased the most, and the increased amount was 216.88%. Conversely, the POD activity of *K. blossfeldiana* increased the least, which was only 28.10%.

In the process of water deficit stress, CAT activity of each plant at different time points also showed significant differences ($P \leq 0.05$). According to Fig. 4 c), with the increase of water deficit time, CAT activity of each plant decreased on the 10th day and increased

Table 1. Wilting rates of the six plant species on days 0, 10, 20, 30 and 40.

Plant species	0 day wilting rate (%)	10 day wilting rate (%)	20 day wilting rate (%)	30 day wilting rate (%)	40 day wilting rate (%)
K. blossfeldiana	0	0	10	53	90
H. erythrostictum	0	0	0	18	76
S. lineare	0	0	0	14	54
P. aizoon	0	0	0	23	49
R. rosea	0	0	0	20	63
S. sarmentosum	0	0	0	49	70

Note: The percentage of withered plants in the total number of plants.

afterward, showing a trend of first decreasing and then increasing. Compared with CAT activity on day 0 and day 40 of the six species, *K. blossfeldiana* showed the largest increase in CAT activity 84.05%. However, CAT activity of *S. sarmentosum* was decreased, reduced by 34.79%.

According to Fig. 4d), there were significant differences in SOD activity of each plant at different time points ($P \leq 0.05$). SOD activity of *K. blossfeldiana*, *S. lineare*, *P. aizoon*, *R. rosea* and *S. sarmentosum* decreased on the 10^{th} day and ascended afterwards, showing a trend of first decreasing and then increasing. The SOD activity of *H. erythrostictum* showed an increasing trend firstly, although decreased on the 40^{th} day, it still showed a higher activity compared with the initial value. Compared with SOD activity on day 0 and day 40 of the six species, SOD activity of *S. sarmentosum* increased the most with 284.39%. On the contrary, the activity of SOD of *P.aizoon* decreased 13.71%.

As can be seen from Fig. 5, there were significant differences in RCC of six species at different time points ($P \leq 0.05$). RCC contents of *H. erythrostictum* and *S. lineare* decreased from 0 to 10 days, increased on the 20^{th} day, and decreased later. However, *K. blossfeldiana*, *P. aizoon*, *R. rosea* and *S. sarmentosum* showed an overall downward trend. Compared with the RCC of the six species on day 0 and day 40, *S. sarmentosum* decreased the most (up to 34.67 SPAD) and *R. rosea* decreased the least (only 8.2 SPAD).

In this experiment, the content of MDA, activities of CAT, POD and SOD of the six species of Crassulaceae generally showed an upward trend with the increase of water deficit degree, while the content of RCC generally showed a downward trend, which was basically consistent with the research conclusion of Lu et al [38]. Moreover, Lu et al. showed that water shortage in the early planting stage of *Sedum* can lead to thinner root size and larger root to stem ratio. These changes in root traits may have a positive impact on the root activity and drought tolerance of green roof plants under water deficit stress, which is the same as the trend of decreasing first and then increasing in this experiment. These results indicated that water deficit stress was beneficial to the growth of Crassulaceae. In the later experiment, the optimal growth state of each plant could be explored by controlling the gradient of the irrigation amount and water deficit degree of plants [39].

Dean and Claire showed that plants with "slow" traits such as relative growth rate, biomass and leaf

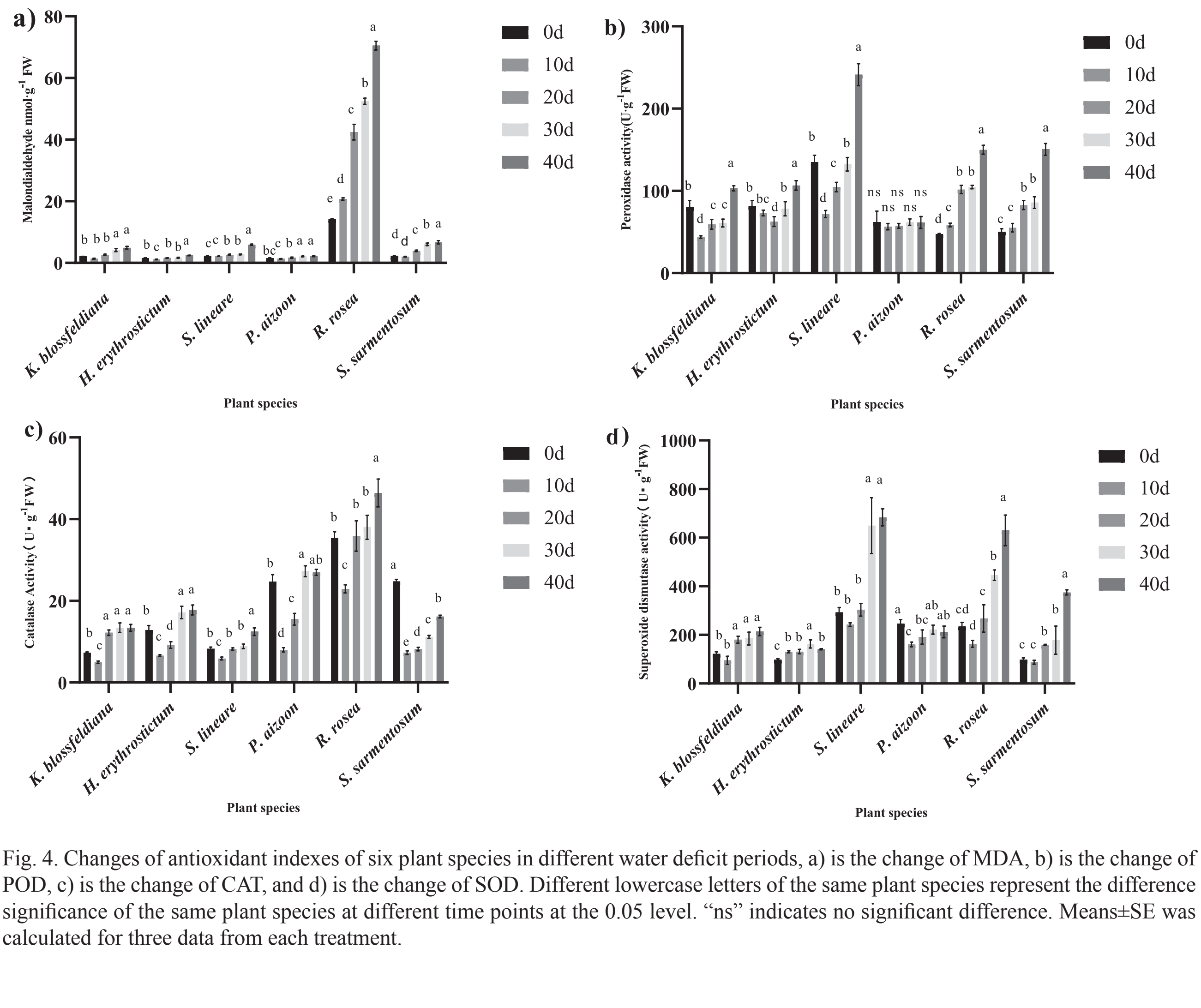

Fig. 4. Changes of antioxidant indexes of six plant species in different water deficit periods, a) is the change of MDA, b) is the change of POD, c) is the change of CAT, and d) is the change of SOD. Different lowercase letters of the same plant species represent the difference significance of the same plant species at different time points at the 0.05 level. "ns" indicates no significant difference. Means±SE was calculated for three data from each treatment.

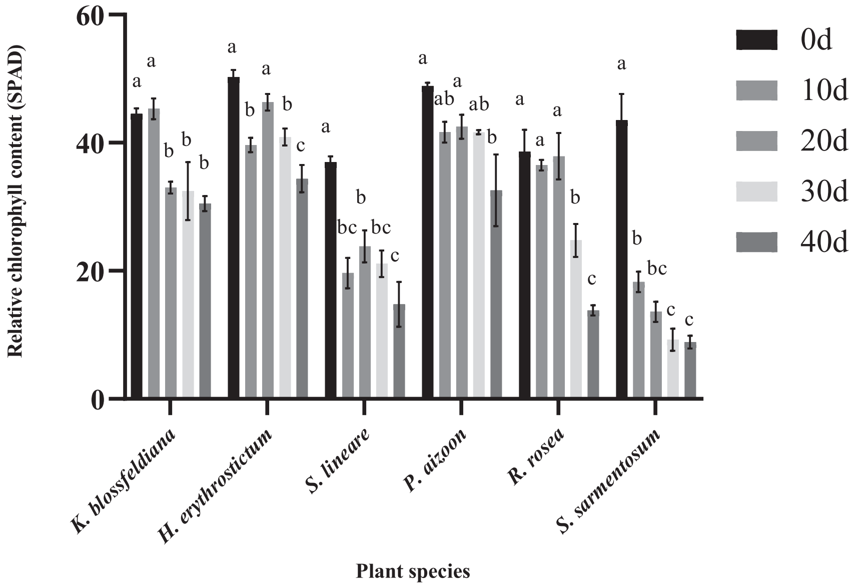

Fig. 5. Changes in RCC of six plant species in different water deficit periods. Different lowercase letters of the same plant species represent the significance of difference at the 0.05 level at different time points of the same plant species. Means±SE was calculated for three data of each treatment.

area need less water and have better drought tolerance than plants with "fast" traits [40]. By setting moderate drought stress, severe drought stress and sufficient water control test, it was found that *Cosmos bipinnata* and *Meehania urticifolia* are not suitable for moderate and severe drought stress and cannot survive [41]. Lu et al. studied the effect of substrate depth on the growth morphology and drought tolerance of *Sedum lineare*, and found that the shallower substrate leads to poor plant growth status and drought tolerance under continuous drought stress [38]. Although in these works the response of plants to drought stress from different perspectives was investigated, they did not involve the change of drought resistance of plants under the continuous drought treatment time under the green roof environment. The changes of MDA content, CAT, POD, SOD activity and RCC of six species of Crassulaceae plants through different water deficit treatment times were determined in this experiment. It was found that with the deepening of water deficit degree, there was no significant difference in POD activity of *P. aizoon*; furthermore, the degree of change of MDA and SOD was also the smallest among the six plant species. Its total SFV ranking was 1, 2, 3, 2 and 2, respectively from 0 to 40 days, and it's pretty high on the list. Besides, through observation of growth state, its state performance was also better. There may be three reasons for this phenomenon: (1) Its own regulatory mechanism enables it to adapt to the increasing degree of water deficit; (2) The increase of ambient air humidity on the roof can significantly affect *P. aizoon* compared with other plants, *P. aizoon* has a stronger ability to absorb water vapor in the air; (3) The sample size of the experiment is not large enough, the next experiment should increase the sample size, and control the relative humidity of the air to further explore and verify the adaptability of *P. aizoon*.

Comprehensive Evaluation of Six Plant Species under Consecutive Water Deficit Conditions

On day 0 of the water deficit treatment (in the state of just watered), the SFV indicated that *S. lineare* was the best performer, the least affected by roof environment. Conversely, *K. blossfeldiana* was the worst performer. Among six plant species, the total SFV of *S. lineare* and *P. aizoon* was much higher than that of the other four plants, furthermore, there was no significant difference in the SFV of the other four plants. On day 0 of water deficit treatment, the growth states of the six plants were: *P. aizoon*>*S. lineare*>*H. erythrostictum*>*S. sarmentosum*>*K. blossfeldiana*>*R. rosea* (as shown in Table 2).

The SFV showed that on the 10th day of water deficit treatment, *S. lineare* performed best and was least affected by water deficit. Instead, *K. blossfeldiana* showed the worst performance, the total SFV was much lower than the other five plants, and the growth status of six plants on the 10th day of water deficit treatment as follows: *H. erythrostictum*>*P. aizoon*>*S. lineare*>*R. rosea*>*K. blossfeldiana*>*S. sarmentosum* (Table 3).

The SFV showed that on the 20th day of water deficit treatment, *S. lineare* performed best and was least affected by water deficit; and *H. erythrostictum* fared worst and was most affected by water deficit. There was no significant difference in SFV between *S. lineare* and *R. rosea* ($P \leq 0.05$), which was much higher than that of the other four plants. Furthermore, there was no significant difference in SFV of the other four plants. The growth status of the six plants on the 20th day of

Table 2. Comprehensive evaluation of six plant species on day 0 based on SFV method.

Plant species	MDA-ASFV	POD-SFV	CAT-SFV	SOD-SFV	RCC-SFV	Total SFV	Rank
K. blossfeldiana	0.95	0.35	0.01	0.15	0.57	2.02	5
H. erythrostictum	0.99	0.36	0.20	0.04	1.00	2.59	3
S. lineare	0.94	0.91	0.04	0.91	0.00	2.80	2
P. aizoon	0.99	0.16	0.60	0.71	0.90	3.36	1
R. rosea	0.01	0.01	0.97	0.65	0.13	1.76	6
S. sarmentosum	0.94	0.04	0.61	0.04	0.49	2.12	4

Table 3. Comprehensive evaluation of six plant species on the 10th day based on SFV method.

Plant species	MDA-ASFV	POD-SFV	CAT-SFV	SOD-SFV	RCC-SFV	Total SFV	Rank
K. blossfeldiana	0.99	0.04	0.02	0.11	1.00	2.15	5
H. erythrostictum	1.00	0.89	0.10	0.31	0.84	3.13	1
S. lineare	0.94	0.85	0.06	0.95	0.05	2.86	3
P. aizoon	0.99	0.41	0.17	0.48	0.92	2.97	2
R. rosea	0.02	0.47	0.95	0.50	0.72	2.65	4
S. sarmentosum	0.95	0.31	0.44	0.08	0.00	1.78	6

Table 4. Comprehensive evaluation of six plant species on the 20th day based on SFV method.

Plant species	MDA-ASFV	POD-SFV	CAT-SFV	SOD-SFV	RCC-SFV	Total SFV	Rank
K. blossfeldiana	0.98	0.10	0.14	0.29	0.59	2.10	5
H. erythrostictum	0.99	0.15	0.05	0.05	1.00	2.24	4
S. lineare	0.97	0.90	0.01	0.90	0.31	3.10	2
P. aizoon	0.99	0.06	0.24	0.34	0.88	2.52	3
R. rosea	0.07	0.85	0.88	0.72	0.74	3.26	1
S. sarmentosum	0.94	0.51	0.02	0.18	0.00	1.65	6

water deficit treatment as follows: *R. rosea*>*S. lineare* >*P. aizoon*>*H. erythrostictum*>*K. blossfeldiana*>*S. sarmentosum* (see Table 4).

On the 30th day of water deficit treatment, the SFV showed that *S. lineare* performed best and was least affected by water deficit. Accordingly, *K. blossfeldiana* received the worst performance, the most affected by water deficit. Compared with each other, the SFV of *S. lineare* was much higher than the other five plants, the six-plant growth status on the 30th day as follows: *S. lineare*>*P. aizoon*>*H. erythrostictum*>*R. rosea*> *K. blossfeldiana*>*S. sarmentosum* (Table 5).

The SFV showed that on the 40th day of water deficit treatment, *S. lineare* performed best and was least affected by water deficit. Moreover, *K. blossfeldiana* had the worst performance and most affected by water deficit. In addition, the SFVs of *S. lineare* and *R. rosea* were much higher than those of the other four plants. On the 40th day of water deficit treatment, the growth states of six plants were: *S. lineare*>*P. aizoon*>*R. rosea*> *H. erythrostictum*>*K. blossfeldiana*>*S. sarmentosum* (see Table 6).

It could be seen from Fig. 6 that the SFV of *S. lineare* and *P. aizoon* ranked between 1-3 when the water deficit degree was light from day 0 to day 20. Furthermore, the SFV of the both plant species still ranked first and second when the water deficit stress was severe from day 30 to day 40. They performed the best adaptability in the whole process and the best ability to adapt to extensive green roof without excessive management. *S. sarmentosum* and *K. blossfeldiana* ranked 4-6 in the SFV under 40-day water deficit stress, with the worst performance. The both were not suitable for extensive green roof and needed further careful management. *R. rosea* ranked first in the SFV on day 20 and performed the best, nevertheless, it demonstrated only moderate performance at the rest of the time. In addition, *H. erythrostictum* only performed the best

Table 5. Comprehensive evaluation of six plant species on the 30th day based on SFV method.

Plant species	MDA-ASFV	POD-SFV	CAT-SFV	SOD-SFV	RCC-SFV	Total SFV	Rank
K. blossfeldiana	0.95	0.06	0.15	0.11	0.72	1.99	5
H. erythrostictum	1.00	0.26	0.27	0.08	0.98	2.58	3
S. lineare	0.98	0.89	0.01	0.80	0.37	3.05	1
P. aizoon	0.99	0.07	0.58	0.16	1.00	2.81	2
R. rosea	0.02	0.57	0.92	0.50	0.87	2.87	4
S. sarmentosum	0.92	0.35	0.08	0.10	0.00	1.45	6

Table 6. Comprehensive evaluation of six plant species on the 40th day based on SFV method.

Plant species	MDA-ASFV	POD-SFV	CAT-SFV	SOD-SFV	RCC-SFV	Total SFV	Rank
K. blossfeldiana	0.96	0.24	0.04	0.13	0.85	2.22	5
H. erythrostictum	1.00	0.26	0.16	0.00	1.00	2.42	4
S. lineare	0.95	0.94	0.02	0.95	0.23	3.09	1
P. aizoon	1.00	0.03	0.42	0.13	0.93	2.50	2
R. rosea	0.02	0.48	0.95	0.86	0.84	3.15	3
S. sarmentosum	0.93	0.48	0.12	0.41	0.00	1.95	6

on the 10th day, and performed moderately at the rest of the time.

In this experiment, considering the ornamental effect and ecological benefits of green roof, it is recommended that the irrigation frequency should be within 10-30 days. From 0 to 30 days, except *K. blossfeldiana* and *S. sarmentosum*, the growth state of the other four plants is observed to be in good condition, which has certain ornamental and ecological value, and so the four plant species are suitable for the application of extensive green roof.

Drought resistance of plants is a characteristic of the interaction between the heritability of plants and the external environment, which needs to be comprehensively reflected by measuring multiple indicators [42, 43]. The application of SFV can remove the one-sidedness caused by a single index. The SFV ranking of the six species demonstrated that *K. blossfeldiana* and *S. sarmentosum* were ranked 4-5 with poor performance. *S. lineare* and *P. aizoon* ranked 1-2 for a long time with good performance. The other four plants were resisted or not resisted at each time point, which was the same as the observed results. It can be seen that the external morphological characteristics of plants can directly show the strength of drought resistance of the tested plants. Water use is closely related to plant biomass, total leaf area and leaf traits, whereas water deficit response is independent of morphological traits. The natural

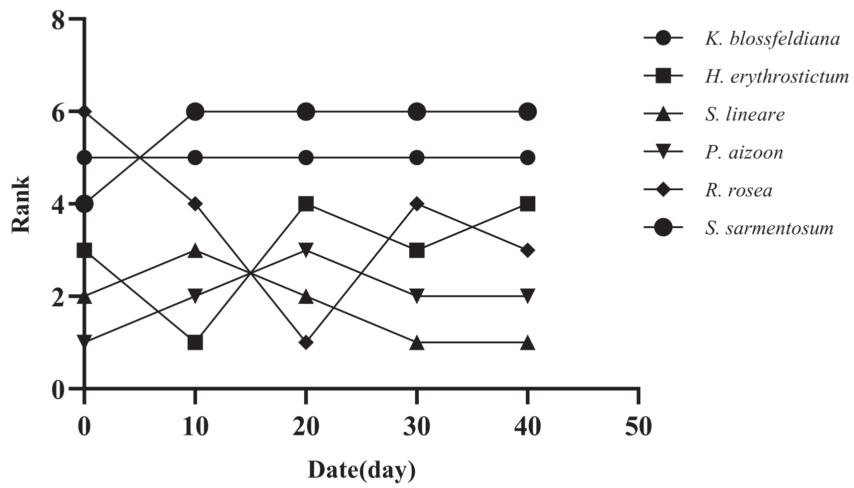

Fig. 6. Comprehensive evaluation ranking of six plant species under consecutive water deficit.

distribution of species does not correspond to their water requirements or water deficit, suggesting that plants from less arid climates may also be suitable for use on green roofs [44]. Selection of species based on traits rather than climate of origin can improve green roof performance and biodiversity by expanding the current plant palette [45]. Through experiments, the external morphological characteristics of plants can be further quantified, their growth indicators can be measured, the mathematical model of drought resistance and external morphological characteristics of plants can be established, the drought resistance of plants can be estimated by the external morphological characteristics of plants, and the database can be established for the plant selection of green roof in various regions [46]. Under the condition of water shortage in summer, some Crassulaceae plants can increase the stress resistance of neighboring plants and reduce the peak soil temperature by 5-7ºC [47]. These results suggest that Crassulaceae can be used to increase the diversity of roof plants. In the future, we can screen out the Crassulaceae plants with better performance, rationally alternate the Crassulaceae plants with common plants, and finally, improve the quality of urban environment.

Conclusions

Among the six species of Crassulaceae used for green roof, *S. lineare* and *P. aizoon* showed the best performance in the whole process. It can be considered to be popularized and applied in extensive green roof. *K. blossfeldiana* and *S. sarmentosum* received the worst performers, the both plant species need certain management measures if considering the application in extensive green roof. In general, they are not suitable for planting in extensive green roof. To increase urban green area, optimize the quality of urban environment and improve residents' living environment, promoting the development of green roof is imminent. Especially, further screening for high resistance of plants applied in the green roof environment is necessary. On the basis of reducing management costs, further exploration is needed to obtain more data to promote the development of green roof in the future.

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Conflict of Interest

The authors declare no conflict of interest.

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