Effects of Light Intensity on Morphological and Physiological Indices of Three Ornamental Varieties of Saxifraga stolonifera (Postprint)

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Abstract

Saxifraga stolonifera is a shade plant with relatively high ornamental value, commonly used in courtyard landscaping. Light intensity may have an important influence on the growth performance of Saxifraga stolonifera, especially leaf color, leaf spot formation, and their color depth, thereby affecting its ornamental value; however, related research has not been reported yet. To investigate the adaptability of different Saxifraga stolonifera varieties to light intensity and understand their optimal canopy density, providing practical guidance for rational utilization, this study used 3 internationally registered Saxifraga stolonifera varieties from China as experimental materials to analyze 100%, 85%, 60%, 40%, and 15% 5 different light intensity treatments on plant growth, development, and photosynthetic physiological indicators. Through principal component analysis, suitable indicators for shade tolerance of Saxifraga stolonifera were screened, and the shade tolerance of Saxifraga stolonifera was comprehensively evaluated using membership function analysis. The results showed that: (1) With increasing shading degree, the number of stolons, leaf number, leaf length, leaf width, leaf area, specific leaf area, chlorophyll a, b, and total chlorophyll content showed an upward trend. (2) With increasing shading degree, aboveground fresh weight, aboveground dry weight, stolon diameter, carotenoid, and flavonoid content showed a trend of first increasing and then decreasing. (3) With increasing shading degree, the initial fluorescence value, soluble sugar, soluble protein, and malondialdehyde content of Saxifraga stolonifera leaves showed a downward trend. (4) The results of principal component analysis and membership function analysis indicated that there were significant differences in the adaptability of the three Saxifraga stolonifera varieties to different light conditions: 'Xuewen' > 'Tianmu Enci' > 'Heikui' , among which the optimal light intensity for 'Xuewen' was 40% light, and the optimal light intensity for

'Tianmu Enci' and 'Heikui' was 15%-40% light. Therefore, in horticultural practice applications, different varieties should be cultivated under different suitable light conditions.

Full Text

Effects of Light Intensity on Morphological and Physiological Indices of Three Ornamental Cultivars of *Saxifraga stolonifera*

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Abstract

Saxifraga stolonifera is a shade-adapted plant with high ornamental value that is widely used in courtyard landscaping. Light intensity may significantly influence its growth performance, particularly leaf coloration and variegation patterns, thereby affecting its aesthetic appeal. However, systematic research on this topic remains scarce. To investigate the light adaptability of different *S. stolonifera* cultivars and determine optimal shade conditions for practical applications, we examined three internationally registered Chinese cultivars under five light intensity treatments (100%, 85%, 60%, 40%, and 15% of full sunlight). We analyzed their effects on plant growth, development, and photosynthetic physiological indices. Principal component analysis was employed to identify suitable indicators for shade tolerance, while membership function analysis was used to comprehensively evaluate shade adaptability across cultivars.

The results showed: (1) With increasing shade, stolon number, leaf number, leaf length, leaf width, leaf area, specific leaf area, and contents of chlorophyll a, chlorophyll b, and total chlorophyll all increased. (2) Aboveground fresh weight, aboveground dry weight, stolon diameter, and contents of carotenoids and flavonoids initially increased then decreased with shading. (3) Initial fluorescence values and contents of soluble sugars, soluble proteins, and malondialdehyde in leaves decreased with increasing shade. (4) Principal component and membership function analyses revealed significant differences in light adaptability among the three cultivars: 'Xue Wen' > 'Tianmu Enci' > 'Hei Kui' . The optimal light intensity was 40% for 'Xue Wen' , and 15%-40% for both

'Tianmu Enci' and 'Hei Kui'. These findings suggest that different cultivars should be grown under specific optimal light conditions in horticultural practice.

Keywords: *Saxifraga*, ornamental cultivar, light intensity, morphological traits, physiological indices, chlorophyll

Introduction

Saxifraga stolonifera (Saxifragaceae) is a perennial herbaceous plant named for its tiger-ear-shaped leaves. Also known as "ear red," "tiger ear," or "golden silk lotus leaf" (Pan, 1992), it is widely distributed across China from Hainan to North China, occurring in forest understories, shrublands, meadows, and moist rock crevices in regions including Hebei, Shaanxi, Gansu, Jiangsu, Anhui, Zhejiang, Central, South, and Southwest China (Wu & Raven, 2001). The entire plant has medicinal value, with effects including heat-clearing, detoxification, dampness removal, swelling reduction, and blood cooling. It has been traditionally used to treat otitis media, traumatic bleeding, toothache, eczema, hematemesis, and prostate hyperplasia with significant efficacy (Pu & Song, 2009). In China, *S. stolonifera* has been extensively utilized for potted ornamentals, bonsai accents, and ground cover in landscaping due to its attractive leaf morphology, coloration, and strong environmental adaptability. Its medicinal and ornamental value has attracted considerable attention from researchers and the public.

Light serves as both the energy source for photosynthesis and a critical factor influencing plant growth and development (Bloor & Grubb, 2003; Kelly et al., 2009). While appropriate light intensity promotes plant growth, excessive light beyond a plant's utilization capacity can damage the photosynthetic system (Takahashi & Badger, 2011). Light adaptability varies among species and even cultivars within the same genus, and photosynthetic characteristics can differ among leaves of different colors on the same plant. For example, Hu et al. (2015) compared chlorophyll fluorescence parameters and rapid light curves of *Rhododendron hybridum* and *R. simsii* after transferring shade-grown plants to full sunlight for five days, revealing differential adaptability between these two *Rhododendron* species. Pan et al. (2021) found that different *Hydrangea macrophylla* cultivars showed variations in photosynthetic characteristics, morphological indices, biomass, leaf water content, chlorophyll content, and osmotic adjustment substances under shading treatments. Wu et al. (2021) measured photosynthetic pigment content, light response curves, and chlorophyll fluorescence parameters in green, variegated, and yellow leaves of *Schefflera odorata* 'Variegata', concluding that all three leaf types exhibited strong shade tolerance, with green and variegated leaves also adapting to certain high-light conditions.

Despite its considerable application value as both a medicinal and ornamental plant, domestic research on *S. stolonifera* has primarily focused on pharmacological activities and cultivation management (Wang et al., 2019; Zhang et al., 2021). Recent reports have documented its application in forest understory greening, desk decoration, rock gardens, wall coverings, wild gardens, vertical greening on shaded walls, urban overpass vertical greening, and vertical shaded flower beds (Kong et al., 2014; Xu & Cheng, 2015). While *S. stolonifera* exhibits strong temperature adaptability across its wide distribution range, light represents the primary environmental stress factor for this typical shade plant, with both excessive and insufficient light causing adverse effects. Previous studies have shown that moderate shading (40%) can alleviate growth inhibition caused by nitrogen deposition and enhance light capture capacity and stress adaptability (Wang et al., 2019), while natural sunlight significantly reduces photosynthetic rate and total chlorophyll content while increasing carotenoid content (He et al., 2010). However, existing research on light intensity responses in *S. stolonifera* remains limited, involving few genetic resources, primarily green or green-white variegated types, and narrow indicator coverage with minimal focus on ornamental traits. Given the high intraspecific diversity and rich variation in leaf color and variegation patterns, determining optimal shade conditions based solely on single-type studies is overly simplistic and poorly representative.

To accelerate the development and landscape application of ornamental *S. stolonifera* resources, comparative studies on light adaptability across multiple cultivars are needed to determine appropriate cultivation conditions. This research established five light gradient treatments to measure growth, development, and photosynthetic physiological indices in three Chinese cultivars. Principal component analysis and membership function analysis were employed to evaluate and compare shade tolerance among cultivars, providing scientific guidance for their promotion and application in landscaping.

Materials and Methods

1.1 Plant Materials Three *S. stolonifera* cultivars ('Hei Kui' , 'Xue Wen' , and 'Tianmu Enci') provided by Shanghai Chenshan Botanical Garden were used in this experiment. 'Hei Kui' , registered in 2014, was China' s first internationally registered *Saxifraga* cultivar (Tian, 2014). 'Xue Wen' and 'Tianmu Enci' were registered by Shanghai Chenshan Botanical Garden in 2020 (details forthcoming). These three cultivars exhibit high ornamental value and significant differences in leaf color and variegation patterns, making them suitable for comparative study. 'Hei Kui' , China' s first independently bred and internationally registered *Saxifraga* cultivar (Tian, 2015; Liu et al., 2017), was recognized as the most promising new variety at the "Second Exchange Conference on New Garden Plant Varieties and Technologies" in Beijing in 2016 (Zhang, 2016). It features rosette-arranged leaves with distinctive eyebrow-shaped black stripes alternating with green areas, offering high ornamental value and horticultural potential. 'Xue Wen' and 'Tianmu Enci' were registered with the International Saxifrage Society in 2020. 'Xue Wen' displays white stripes of varying widths alternating with green, while 'Tianmu Enci' is a newly selected cultivar with dark green and black stripe variegation (more light-sensitive), densely covered with pinkish long hairs, vigorous growth, and high ornamental value, though not yet widely promoted.

One-year-old plants of each cultivar were transplanted into plastic pots (15 cm top diameter, 12 cm bottom diameter, 12 cm height) with one plant per pot. The substrate consisted of peat:perlite:garden soil at a ratio of 8:1:1. Plants were maintained under conventional management in a greenhouse at the Hunan Agricultural University flower base, with sprinkler irrigation once per week. After three months, uniform, pest-free plants were selected for subsequent light treatments.

1.2 Experimental Design and Measurements The shading experiment was conducted from mid-April to mid-June 2021 at the Hunan Agricultural University flower base. Different specifications of construction dust nets and shade nets were used to build four-sided shade frames (1.5 m length × 1.2 m width × 0.75 m height). Five shade treatments were established: 100% (CK), 85% (T1), 60% (T2), 40% (T3), and 15% (T4) of natural light intensity. Light intensity was measured using a Taiwan TES 1332A illuminometer on five sunny days and five cloudy days between 8:00–17:00. Shade percentage was calculated as: 1 - (average light intensity under treatment / average light intensity under full sunlight × 100%). Each cultivar had ten replicates per treatment. The experiment employed a split-plot design with shade level as the main factor and cultivar as the sub-factor.

Morphological indices were measured as follows: At 40 days after treatment, six mature south-facing leaves were randomly harvested for measurement of leaf area, length, and width. At 60 days after treatment, leaf number, stolon number, and stolon diameter were recorded. Stolon diameter was measured with electronic calipers at 3–5 cm from the attachment point. Leaf area, length, and width were determined from photographs using Photoshop 2020. Leaf and stolon numbers were counted directly. Six randomly selected pots per treatment were measured, with results averaged.

Physiological indices were measured at different time points: Photosynthetic pigment content was determined using ethanol extraction at 40 days after treatment (Li, 2000). Anthocyanin and flavonoid contents were measured using 1% HCl-methanol extraction (Mita et al., 1997). At 50 days after treatment, chlorophyll fluorescence was measured on mature leaves using a Pen FP 110 handheld fluorometer (Czech Republic) with OJIP (Kupper et al., 2019) and NPQ3 programs. At 60 days after treatment, soluble sugar content (anthrone colorimetry), soluble protein content (Coomassie brilliant blue method), and malondialdehyde (MDA) content (thiobarbituric acid method) were determined using assay kits from Shanghai Youxuan Biotechnology. Specific leaf area (SLA) and aboveground fresh weight (FW) and dry weight (DW) were measured from six seedlings per treatment.

1.3 Statistical Analysis Data were organized using Microsoft Excel. SPSS 21 software was used for analysis of variance and significance testing ($P < 0.05$) with Duncan' s multiple range test. Origin Pro 2019b and Photoshop 2020 were used for figure preparation and image processing. The membership function method of fuzzy mathematics (Huang et al., 2011) was employed to calculate membership function values for evaluating light adaptability of the three cultivars.

Membership function values (Uij) were calculated as: Uij = (Xij - Ximin) / (Ximax - Ximin) for indicators positively correlated with shade tolerance, and Uij = 1 - (Xij - Ximin) / (Ximax - Ximin) for negatively correlated indicators, where Xij is the measured value of indicator j for cultivar i, Ximin is the minimum value, and Ximax is the maximum value for indicator j. Comprehensive evaluation values (D) were calculated as the average of membership function values across all indicators.

Results

2.1.1 Phenotypic Responses Shading significantly affected plant morphology in all three cultivars (Figure 1). With decreasing light intensity, leaf area, length, and width increased across all cultivars, though leaf length differences in 'Xue Wen' were not significant among treatments. Leaf number increased with shading in 'Hei Kui' and 'Tianmu Enci', reaching maximum values at T4, though not significantly different from T3. In contrast, 'Xue Wen' showed maximum leaf number at T3, with a slight decrease at T4 (not significant). 'Xue Wen' produced the most leaves at T3, followed by 'Hei Kui' and 'Tianmu Enci', with significant differences between 'Xue Wen' and 'Tianmu Enci' but not between 'Hei Kui' and the other two cultivars.

Stolon number increased then decreased with shading in all cultivars, peaking at T3. Mean stolon numbers per pot at T3 were 12.33, 11.67, and 11.00 for 'Hei Kui', 'Xue Wen', and 'Tianmu Enci', respectively, with no significant differences among cultivars at the same light level. Stolon diameter followed a similar trend, peaking at T2 for all cultivars (2.62 mm, 2.34 mm, and 1.71 mm for 'Hei Kui', 'Xue Wen', and 'Tianmu Enci', respectively). 'Hei Kui' and 'Xue Wen' had significantly larger stolon diameters than 'Tianmu Enci' under CK, T1, T2, and T3 treatments. At T4, all three cultivars differed significantly in stolon diameter: 'Hei Kui' > 'Xue Wen' > 'Tianmu Enci' (2.02 mm, 1.59 mm, and 1.20 mm, respectively).

2.1.2 Fresh Weight, Dry Weight, and Specific Leaf Area Light treatments significantly affected fresh weight (FW), consistent with previous studies (Gui, 2008). In 'Hei Kui' and 'Xue Wen', FW increased then decreased with shading, peaking at T3 (31.40 g and 54.92 g, respectively). At T4, FW decreased by 23.76% and 15.33% compared to T3, with significant differences among T2, T3, and T4 in 'Hei Kui' but not in 'Xue Wen'. In 'Tianmu Enci', FW increased gradually with shading, reaching maximum (29.21 g) at T4, though differences between T3 and T4 and between T3 and T2 were not significant. Under CK and T1, 'Xue Wen' had significantly higher FW than 'Hei Kui', while differences between 'Tianmu Enci' and the other cultivars were not significant. At 15%-60% light intensity, 'Xue Wen' showed significantly higher FW than both 'Hei Kui' and 'Tianmu Enci' (Figure 2A).

Dry weight (DW) responses differed among cultivars (Figure 2B). All three cultivars showed initial increases then decreases in DW with shading, peaking at T3 (3.40 g, 4.79 g, and 2.17 g for 'Hei Kui', 'Xue Wen', and 'Tianmu Enci', respectively). In 'Hei Kui', T3 DW was significantly higher than T2 and T4. In 'Xue Wen', DW at T2 was 20.88 g lower than at T3 (not significant), while T4 DW was 39.46% lower than T3 (significant). In 'Tianmu Enci', T3 DW was higher than T2 and T4, but differences were not significant.

Specific leaf area (SLA) reflects a plant' s capacity to acquire light resources under different habitats (An, 2015). As a shade plant, *S. stolonifera* under CK treatment suffered leaf burn before full development, resulting in SLA of 0 $cm^2 \cdot g^{-1}$. SLA increased linearly with decreasing light intensity across all cultivars, with significant differences between T4 and T1/T2/T3 treatments, but not between T1 and T2. Maximum SLA values at T4 were 9.87, 8.51, and 4.98 $cm^2 \cdot g^{-1}$ for 'Tianmu Enci', 'Xue Wen', and 'Hei Kui', respectively, with significant differences between 'Tianmu Enci' and 'Hei Kui', but not between 'Xue Wen' and the other cultivars (Figure 2C).

2.2.1 OJIP Curves OJIP curves (chlorophyll fluorescence induction kinetics) revealed that fluorescence at inflection points I and peak P exceeded that at origin O and inflection point J across all light treatments (Figure 3). In 'Hei Kui', fluorescence at J, I, and P points decreased substantially under CK and T1 compared to T2, T3, and T4, indicating severe damage to Photosystem II (PS II) activity. Similarly, in 'Tianmu Enci', CK treatment showed markedly lower fluorescence at these points compared to all other treatments. The timing of maximum fluorescence (Fm) differed among treatments: 'Hei Kui' and 'Tianmu Enci' reached Fm earliest at T4, while 'Xue Wen' peaked at T3.

2.2.2 PS II Efficiency Initial fluorescence (Fo) responses varied among cultivars under different shade conditions (Table 2). Minimum and maximum Fo values occurred at T4 and T1 for 'Hei Kui', at CK and T4 for 'Xue Wen', and at T3 and CK for 'Tianmu Enci'. Fo represents fluorescence yield when PS II reaction centers are fully open, and its magnitude relates to chlorophyll concentration, suggesting differential chlorophyll responses to light intensity among cultivars.

Maximum fluorescence (Fm) increased with shading in all cultivars, peaking at T4. However, Fm values differed slightly: 'Xue Wen' > 'Tianmu Enci' > 'Hei Kui' (69,020.50, 61,456.33, and 54,943.00, respectively), with significant differences between 'Hei Kui' and 'Xue Wen' but not between 'Tianmu Enci' and the other cultivars.

Maximum photochemical quantum efficiency of PS II (Fv/Fm) reflects long-term adaptation mechanisms, remaining relatively stable under normal growth conditions but declining under environmental stress (Tang et al., 2020). No significant differences in Fv/Fm were observed among cultivars under the same light level (T2, T3, T4). Both 'Hei Kui' and 'Tianmu Enci' showed increasing Fv/Fm with decreasing light, peaking at T4 (0.801 and 0.795, respectively). In contrast, 'Xue Wen' peaked at T3, then declined at T4. These results indicate that 'Hei Kui' and 'Tianmu Enci' achieved maximum photochemical efficiency at T4, while 'Xue Wen' peaked at T3, with other treatments causing varying degrees of stress-induced Fv/Fm reduction.

2.2.3 Photochemical and Non-photochemical Quenching Coefficients Photochemical quenching coefficient (Qp) represents the proportion of light energy absorbed by PS II antenna pigments used for photochemical electron transport. Higher Qp values indicate greater PS II electron transport activity and more open reaction centers, enabling more efficient photosynthetic electron transfer (Shi et al., 2004; Zhang et al., 2005). As shown in Figure 4, Qp in 'Hei Kui' under CK was lower than under T1 and T2 during the first 200 s of light adaptation, indicating that both high light and deep shade reduced PS II electron transport activity. In 'Xue Wen' and 'Tianmu Enci', Qp under T3 and T4 was lower than under CK, T1, and T2, suggesting reduced electron transport under these shade treatments. Comparing maximum Qp values, 'Hei Kui' and 'Xue Wen' peaked at T1, while 'Tianmu Enci' peaked at CK, indicating that all cultivars maintained relatively high photosynthetic electron transport activity under mild light stress.

Non-photochemical quenching coefficient (NPQ) reflects the dissipation of excess absorbed light energy as heat, serving as a photoprotective mechanism that prevents photosynthetic apparatus damage from excessive light absorption (Shi et al., 2004; Yang et al., 2010). NPQ analysis (Figure 5) showed that at 40 s after light adaptation, NPQ in CK-treated 'Xue Wen' and CK- and T1-treated 'Hei Kui' and 'Tianmu Enci' decreased markedly, indicating photosynthetic apparatus damage from excess light energy. Maximum NPQ values were observed in 'Hei Kui' under T4 and T2, in 'Xue Wen' under T2, and in 'Tianmu Enci' under T3, suggesting that mild shading does not impair photoprotective mechanisms.

2.3 Effects of Shading on Leaf Phenotype, Photosynthetic Pigments, and Secondary Metabolites Leaf appearance varied among light treatments (Figure 6). With decreasing light intensity, black variegation area in 'Hei Kui' expanded and darkened while green areas decreased in size and deepened in color. In 'Xue Wen', white stripe area along leaf veins increased and leaf color shifted from light to dark green. In 'Tianmu Enci', irregular brown variegation between veins and leaf color changes were less pronounced. Leaf scorching occurred in 'Xue Wen' and 'Tianmu Enci' under CK, T1, and T2, and in 'Hei Kui' under CK and T1, with 'Tianmu Enci' showing the most severe damage.

Photosynthetic pigment analysis (Figure 7) revealed that chlorophyll a, chlorophyll b, and total chlorophyll in 'Hei Kui' variegated areas increased then decreased then increased again with shading, though differences between T3 and T2 were not significant. In 'Hei Kui' green areas, these pigments decreased then increased, with non-significant differences between CK and T1. In 'Xue Wen' , all chlorophyll parameters increased consistently with shading. In 'Tianmu Enci' , chlorophyll content showed irregular responses to light intensity, with minimal differences among treatments but maximum values at T4. Under T3 and T4 shading, chlorophyll content ranked: 'Xue Wen' > 'Hei Kui' > 'Tianmu Enci' .

Carotenoid, flavonoid, and anthocyanin contents also responded to shading (Figure 7). Carotenoids in 'Hei Kui' variegated areas and 'Xue Wen' increased then decreased, peaking at T2 and T3, respectively, with minimum values at CK. In 'Hei Kui' green areas, carotenoid content under T2, T3, and T4 exceeded that under CK and T1, while in 'Tianmu Enci' , CK showed significantly higher carotenoids than other treatments. Flavonoid content in 'Hei Kui' (both variegated and green areas) and 'Tianmu Enci' increased then decreased with shading, with 'Tianmu Enci' showing a 92.18% reduction from T1 to T4. Anthocyanin content in 'Hei Kui' variegated areas was significantly higher than other tissues and increased with shading. In 'Hei Kui' green areas, anthocyanins peaked at T1, while in 'Xue Wen' they peaked at CK. 'Tianmu Enci' showed irregular anthocyanin responses to light intensity.

2.4 Effects of Shading on Physiological Indices Soluble sugar content decreased with shading in all cultivars compared to full light (Figure 8A). 'Xue Wen' showed the greatest reduction (79.47%), followed by 'Hei Kui' (51.95%) and 'Tianmu Enci' (47.19%). Under CK, T1, T2, and T3, soluble sugar content was highest in 'Xue Wen' , followed by 'Hei Kui' and 'Tianmu Enci' (all significant). At T4, 'Hei Kui' had significantly higher soluble sugar content than 'Xue Wen' and 'Tianmu Enci' , which did not differ significantly. Within cultivars, 'Hei Kui' and 'Tianmu Enci' showed no significant differences among CK, T1, T2, and T3, but all differed significantly from T4. The fastest decrease occurred between T3 and T4 across all cultivars.

Soluble protein content decreased with shading in 'Hei Kui' and 'Tianmu Enci' , while 'Xue Wen' showed an initial decrease then increase, reaching minimum (347.25 $g \cdot mL^{-1}$) at T3 (Figure 8B). This suggests that shading accelerated soluble protein consumption in 'Hei Kui' and 'Tianmu Enci' , while moderate and severe shading slowed protein accumulation in 'Xue Wen' , with 40% light intensity promoting protein accumulation.

Malondialdehyde (MDA) content decreased with shading in 'Hei Kui' and 'Tianmu Enci' , while 'Xue Wen' showed an initial decrease then increase, reaching minimum at T3 (Figure 8C). In 'Xue Wen' , CK and T1 differed significantly from T2, T3, and T4.

2.5 Comprehensive Evaluation of Light Adaptability Morphological and photosynthetic physiological indices varied among the three cultivars under different light treatments. To evaluate light adaptability, representative data from T4 treatment were selected for comprehensive assessment. SPSS 21 was used to standardize morphological and photosynthetic physiological indices, followed by principal component analysis.

Four principal components explained 88.89% of total variance (Table 3). Principal component 1 (35.33% variance) included leaf length, leaf width, leaf area, FW, Fm, Fo, total chlorophyll, and chlorophyll a (eight indicators). Principal component 2 (18.73%) included soluble protein, SLA, stolon diameter, and stolon number (four indicators). Principal component 3 (18.51%) included leaf number, chlorophyll b, and soluble sugar (three indicators). Principal component 4 (16.32%) included carotenoids, Fv/Fm, and flavonoids (three indicators). Eighteen indicators with loadings above 0.6 were initially selected. After removing redundant indicators with correlation coefficients exceeding 0.90 (Zhang & Zhao, 2013), twelve final indicators were retained: leaf area, FW, Fo, total chlorophyll, soluble protein, SLA, stolon diameter, stolon number, leaf number, carotenoids, Fv/Fm, and flavonoids.

2.5.2 Membership Function Analysis Standardized values of selected indicators were used to calculate membership function values for the three cultivars under 15% light treatment (Table 4). Higher values indicate greater shade tolerance. Ranking of shade tolerance was: 'Xue Wen' > 'Tianmu Enci' > 'Hei Kui' .

Discussion and Conclusion

Plant morphological plasticity represents a crucial adaptation to variable environments. As the primary photosynthetic organ and the most plastic organ during plant evolution, leaves adjust morphology to adapt to light conditions (Xue et al., 2011). Our results demonstrate that light intensities above 60% caused leaf scorching, with plants under full sunlight unable to grow normally or even survive. With increasing shade, leaf area and SLA increased gradually, likely enabling *S. stolonifera* to capture more light in shaded environments by developing larger, thinner leaves that increase light interception area and reduce radiation penetration distance, thereby improving light use efficiency. This pattern aligns with findings in *Alhagi sparsifolia* (Ma et al., 2018).

Stolon propagation is a primary reproduction method for *S. stolonifera* in both natural and artificial settings, making stolon number and diameter critical for population expansion. Our results indicate that 60% and 40% light intensities are optimal for stolon development and individual proliferation. Based on biomass and leaf number, 40% light was optimal for 'Hei Kui' and 'Xue Wen' , suggesting that moderate shading ensures normal growth, while excessive shading reduces biomass. In contrast, 15% light was more suitable for 'Tianmu Enci' , indicating its higher optimal shade level, possibly related to its natural distribution in higher altitude habitats with weaker understory light, providing valuable insights for horticultural applications.

Chlorophyll fluorescence non-destructive detection technology is widely used to study photosynthetic physiology and stress responses. Fluorescence parameters reflect light energy absorption, transfer, and dissipation in PS II (Stephen & Donna, 2011; Nan & Lin, 2019). Increased Fo can prevent irreversible damage to PS II reaction centers. Differential responses of Fo and NPQ among cultivars indicate that both full sunlight and excessive shade (15%) damaged PS II centers. Variations in OJIP curves further confirmed severe PS II damage in 'Hei Kui' under full sunlight and 85% light, and in 'Tianmu Enci' under full sunlight. Maximum Fm values under deep shade (15%) suggest that *S. stolonifera* maintains high electron transport efficiency in highly shaded environments, with efficiency ranking: 'Xue Wen' > 'Tianmu Enci' > 'Hei Kui' . Normal Fv/Fm values for healthy plants range from 0.75–0.85 (Zhang et al., 2014). In our study, Fv/Fm values below 0.75 in 'Hei Kui' under 40%-100% light and in 'Xue Wen' and 'Tianmu Enci' under full sunlight and 85% light indicate photoinhibition and light stress, confirming that *S. stolonifera* requires shaded conditions for optimal growth.

Plants adapt to fluctuating light by adjusting pigment composition and content, which can be used to assess light adaptability (Ma et al., 2018). Chlorophyll and carotenoids are the two major pigments involved in light absorption, transfer, and conversion (Sun et al., 2010). In our study, chlorophyll content in 'Hei Kui' and 'Xue Wen' generally increased with shading, similar to findings in *Lonicera maackii* seedlings (Xue, 2019). However, 'Tianmu Enci' showed significant differences only between 15% light and other treatments. Carotenoid content in 'Hei Kui' and 'Xue Wen' showed significant, treatment-dependent changes, while 'Tianmu Enci' showed minimal variation, suggesting that 'Hei Kui' and 'Xue Wen' actively adapt photosynthetic pigments to light environments, whereas 'Tianmu Enci' shows poorer adaptability.

Carotenoids, anthocyanins, and flavonoids are important biochemical strategies for avoiding photoinhibition and protecting photosynthetic organs (Voss et al., 2013). Our findings reveal that 'Hei Kui'employs multiple protective mechanisms through carotenoids, flavonoids, and anthocyanins. 'Xue Wen' , with low and light-insensitive anthocyanin content, primarily adjusts carotenoid and flavonoid levels. 'Tianmu Enci' mainly modulates anthocyanin and flavonoid contents. These differences in pigment adjustment strategies among cultivars with varying leaf colors and variegation patterns result in differential light adaptability.

Soluble sugars, crucial carbon sources from photosynthesis, maintain membrane integrity, regulate osmotic pressure, and enhance stress resistance (Wang et al., 2017). Our results show that soluble sugar content decreased with shading in all cultivars, indicating that shading is unfavorable for sugar accumulation but promotes consumption, consistent with Liu et al. (2006). MDA, a product of membrane lipid peroxidation, reflects membrane damage and stress resistance (Zhang et al., 2013). Soluble proteins protect cellular components and membranes. In 'Hei Kui' and 'Tianmu Enci', soluble protein and MDA contents decreased with shading, while in 'Xue Wen', both reached minimum at 40% light then increased at 15% light. This suggests that excessive light caused membrane damage and lipid peroxidation in 'Hei Kui' and 'Tianmu Enci', inducing soluble protein synthesis to mitigate damage. For 'Xue Wen', both excessive and insufficient light increased MDA and soluble protein content, with minimum values at 40% light indicating minimal stress.

In conclusion, different ornamental *S. stolonifera* cultivars adapt to strong or weak light stress by modulating leaf morphology and adjusting photosynthetic pigment and secondary metabolite contents, but exhibit differential phenotypic, physiological, and biochemical responses and light adaptability. Membership function analysis based on selected indicators revealed that 'Xue Wen' is the most shade-tolerant with the broadest light adaptability, making it suitable for wider cultivation. Its optimal light intensity is 40%. 'Tianmu Enci' and 'Hei Kui' have slightly lower tolerance to strong or weak light, requiring more restricted cultivation ranges, with optimal light intensity between 15%–40%. Horticultural applications should therefore consider the specific optimal light intensity ranges and microenvironments for each cultivar.

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Note: Figure translations are in progress. See original paper for figures.