FUNCTIONAL TRAITS AND ECOLOGICAL ADAPTATION OF GARDEN PLANTS BASED ON LEAF ECONOMICS SPECTRUM

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Abstract. Garden plants are important components of urban ecosystems. Their ecological adaptability is directly affected by their leaf functional traits. The Leaf Economics Spectrum shows potential in revealing trade-off strategies between resource acquisition and conservation in plants. This study selects ten typical garden plants within the Leaf Economics Spectrum framework. It systematically measures leaf morphological structure and physiological trait indicators. Through correlation analysis and principal component analysis, it deeply explores the functional trait characteristics and ecological adaptation of garden plants. Research findings indicate significant differences among plant species in traits such as specific leaf area and leaf dry matter content. Correlation analysis reveals a significantly positive correlation between specific leaf area and nitrogen content, as well as a significant positive correlation between plant leaf dry matter content and the carbon-to-nitrogen ratio. Principal component analysis further extracted three principal components that collectively explained the majority of trait variation. Membership function results indicated lower adaptive levels for the Nephrolepis, while the Hibiscus rosa-sinensis and Canna exhibited the highest ecological adaptability. This study provides theoretical foundations for the scientific configuration of landscape plants, offering significant practical value for optimizing urban ecosystem services and enhancing the sustainability of green spaces.
Keywords: *functional diversity, urban stress, resource allocation, membership function, artificial selection*

Introduction

Plants are fundamental components of urban ecosystems. Beyond their aesthetic value in enhancing cityscapes, they play irreplaceable ecological roles in carbon sequestration and oxygen production, air purification, and the maintenance of biodiversity (Schmitz et al., 2024; Mengist and Asfaw, 2023). As the pace of urbanization continues to accelerate, garden plants are increasingly subjected to intensified environmental stressors (Géron et al., 2024). De Almeida et al. (2024) found that urbanization intensity significantly affected both the height and abundance of urban vegetation. As urbanization intensity increased, plant height and functional traits values decreased noticeably. In another study, Zhong et al. (2025) observed that functional traits such as leaf area, stomatal conductance, and transpiration rate varied significantly along the urban–rural gradient. These variations reflected differences in growth forms and functional adaptations across plant species. Collectively, these findings underscore the influence of urban environments on plant traits and, in turn, on ecological adaptability. However, there is currently limited research on how garden plants balance between resource acquisition and conservation under such pressures.

Environmental variability, particularly changes in land use and climate conditions, can pose significant challenges to the growth and development of urban garden plants.

Beheshti et al. (2023) demonstrated that drought stress notably impacted both aboveground and belowground biomass in five landscape plant species. Insufficient water availability significantly reduced dry matter content and leaf area, while root biomass increased as a response to drought. Similarly, Yang et al. (2023) measured changes in traits such as leaf area, fresh weight, and dry weight under drought conditions and found that both dry weight and leaf area declined significantly. Furthermore, light intensity significantly influenced leaf morphology, with high light conditions associated with higher nitrogen-to-phosphorus ratios compared to low light environments. These studies reveal the varied adaptive strategies plants employ under environmental stress, yet the underlying trade-off mechanisms remain poorly understood.

The Leaf Economics Spectrum (LES) serves as a framework for describing the patterns of variation in functional traits of plant leaves. It categorizes leaf traits into two terminal types: "rapid investment-return" and "slow investment-return," corresponding respectively to strategies for rapid resource acquisition in high-resource environments and long-term resource conservation in low-resource environments. This framework is applicable for analyzing plant adaptation strategies in complex environments, particularly revealing the balancing mechanisms governing resource allocation and utilization. Rychtecká et al. (2024) employed LES to investigate biodiversity in semi-arid grasslands in the Czech Republic, estimating average species persistence from initial species composition and examining the effects of seeding richness and composition on persistence and regional dispersal. Pahadi et al. (2024) studied the temporal stability of LES traits in wild blueberries, focusing on leaf structure, photosynthetic capacity, and chemical composition. They found that cumulative multi-year environmental changes led to shifts in trait expression. Da Sois et al. (2024) explored physiological responses such as stomatal conductance and relative leaf water content in 20 Mediterranean woody species. Their findings indicated that drought-tolerant species exhibited limited water regulation through stomata but showed pronounced adjustments in relative leaf water content. These studies confirm that LES offers a systematic framework for analyzing plant resource use strategies. However, research applying this framework specifically to garden plants—particularly in the context of functional traits variation and ecological adaptability—remains scarce.

In summary, existing research has made significant progress in understanding the relationship between functional traits of plant leaves and ecological adaptability, with the leaf economic spectrum theory emerging as a key research focus in this field. However, studies investigating the functional traits and ecological adaptability mechanisms of ornamental plants within the leaf economic spectrum framework remain notably underdeveloped. Therefore, this study innovatively applies the leaf economic spectrum to examine the functional traits and ecological adaptability of ornamental plants. First, ten representative native ornamental plant species from the study region were selected. Key functional trait indicators-including leaf morphological structure, physiological characteristics, and elemental content-were measured. Combining analysis of variance (ANOVA), correlation analysis, and principal component analysis (PCA), the positions of different ornamental plants within the leaf economic spectrum were quantified. Finally, the relationship between their functional traits and ecological adaptability was explored. This study aims to clarify whether significant differentiation patterns exist in the leaf economic spectrum for functional traits of ornamental plants and how variations in these traits reflect their ecological adaptability to urban environments. The findings are expected to provide theoretical foundations for ornamental plant breeding and landscape design while expanding the application value of the leaf economic spectrum within ecosystems.

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Methods and materials

Basic theory of leaf economics spectrum and overview of study area

Basic theory of leaf economics spectrum

The study selects the LES as the basic framework for analyzing plant functional traits and ecological adaptability. The LES theory holds that significant trade-off relationships exist among leaf traits. By organizing the LES framework, it comprehensively integrates coordinated variations among plant traits and reveals plant adaptation strategies to different ecological environments. LES has become the mainstream theoretical framework for describing plant leaf functional traits (Wang and Dang, 2024). The concept of LES is shown in *Figure 1*.

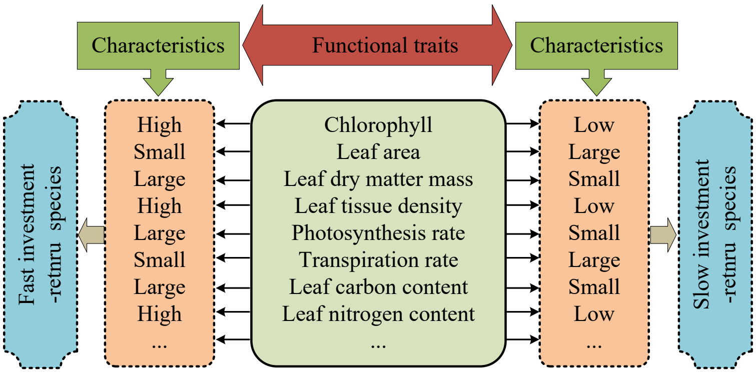

Figure 1. *Conceptual diagram of LES*

As shown in *Figure 1*, core LES traits include leaf area, photosynthetic rate, and nitrogen content. Plants with high leaf area and high photosynthetic rate usually belong to fast-investment, high-return species. Plants with small leaf area, weak photosynthetic ability, and low leaf nitrogen content belong to slow-investment, low-return species (Heckman et al., 2025). LES reflects a gradient change from “fast investment-high return” strategies to “conservative investment-low consumption” strategies. This indicates that different species balance resources according to their own needs to adapt to ecological changes (Nadal et al., 2023).

Overview of study area

The study area is located in the southeastern coastal region of China, at 30° 16’ N, 120° 12’ E. The regional topography exhibits a typical “high in the west, low in the east, with mountains and water intertwined” pattern. Most areas, including the eastern main urban district, consist primarily of low-altitude plains with an average elevation of 12 m. This flat terrain, crisscrossed by a dense river network, serves as the concentrated distribution zone for urban built-up areas and artificial wetlands. The western region comprises hilly and mountainous terrain, with the highest peak reaching 413 m above sea level. The study area exhibits diverse ecosystem types with distinct hierarchical structures. Plains are dominated by urban wetland ecosystems, while the western hills are primarily covered by subtropical evergreen broadleaf forests. These forests interact with extensive bamboo groves and tea plantations to form complex agroforestry systems. The plane map of the study area and sampling sites is shown in *Figure 2*.

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Figure 2. *Study area and sampling sites. (Source: https://bajiu.cn/ditu/?id=491)*

As shown in *Figure 2*, the study area lies on the southern wing of the Yangtze River Delta, with dense water networks and good ecological environment. Due to its special geographic location, the vegetation resources are extremely rich. The selected sampling sites are mainly located in the main urban area, including the botanical garden, lakes, and forest park, where garden plant species are relatively stable. The botanical garden, established in 1956, cultivates over 3000 plant species with a relatively stable assortment of ornamental plants. The terrain slopes from northwest to southeast, featuring alternating hills and valleys at elevations ranging from 10 to 165 m. The soil consists of red and yellow soils with a pH level of 4.9-6.5 and moderate fertility. The lake scenic area lies west of the study site's urban district, situated at the junction of plains, hills, and coastal waters, surrounded by rich and diverse vegetation. This region is enclosed by mountains on three sides and borders the urban area on one side. The surrounding peaks do not exceed 400 m in height, with the outer ring composed of quartz sandstone and the inner ring of limestone. The Forest Park is situated north of the city. Originally an industrial wasteland with less than 60% vegetation coverage in 2005, it has been transformed into an ecological barrier for the northern city area. A total of 671 plant species belonging to 440 genera across 143 families have been recorded here. The climate belongs to the subtropical monsoon zone, featuring warm and humid conditions with distinct seasons. The average monthly temperature and precipitation over multiple years are shown in *Figure 3*.

Figure 3a shows that January has the lowest average temperature at 4.6°C, while July has the highest at 28.9°C. *Figure 3b* shows the annual average precipitation is 1450 mm, with the rainy season from May to September accounting for 70% of the total rainfall. The special climate conditions make the plant resources especially rich. Common tree-type garden plants include Cinnamomum camphora, Ginkgo biloba, and Salix babylonica. Common shrubs include Rhododendron simsii, Lagerstroemia indica, and

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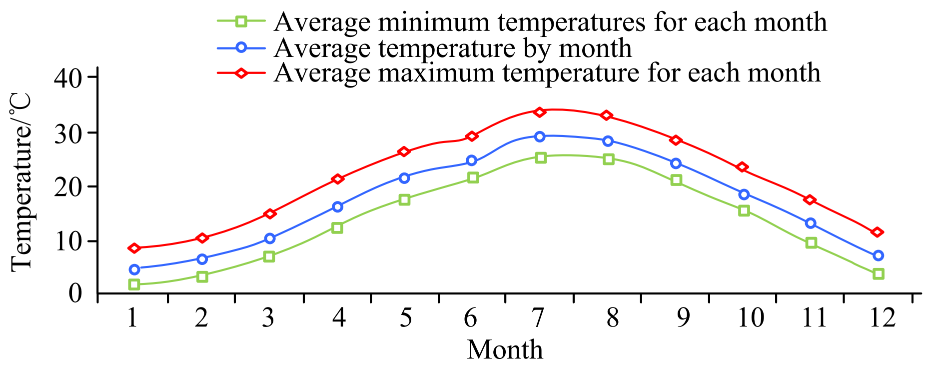
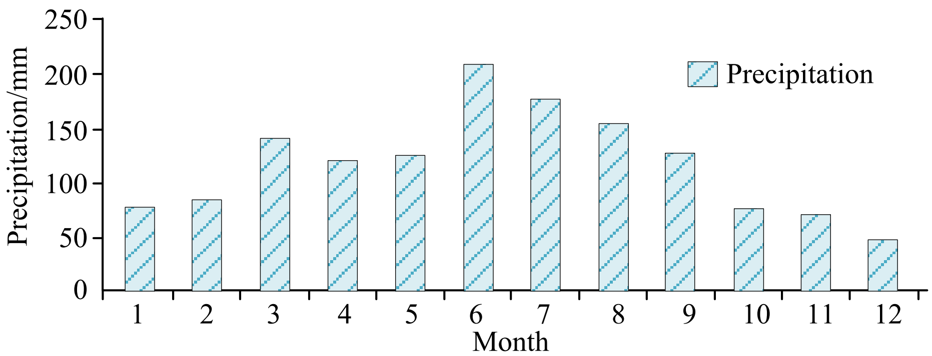
Nandina domestica. Herbaceous garden plants include Liriope spicata, Iris tectorum, and Nephrolepis cordifolia. The functional traits of these species is shaped by both urban environmental stresses and human aesthetic demands. Simultaneously, landscape plants in natural habitats face unique compound stresses such as heat island effects, soil compaction, and intermittent drought—conditions fundamentally different from those experienced by wild species in their natural environments. Therefore, this study employs the LES framework to systematically analyze resource trade-off patterns in ornamental plants under urbanization, aiming to provide scientific basis for their selection and landscape design. The specific plant species are listed in *Table 1*.



(a) Annual average temperature



(b) Annual average precipitation

Figure 3. *Multi-year average monthly temperature and precipitation statistics*

Table 1. *Specific study objects*

Number	Plant name	Latin name/abbreviation	Lifestyle
1	Banyan tree	*Ficus microcarpa, FM*	Trees
2	Camphor tree	*Cinnamomum camphora, CC*	Trees
3	Bombax	*Bombax ceiba, BC*	Trees
4	Phoenix tree	*Delonix regia, DR*	Trees
5	Azalea tree	*Rhododendron simsii, RS*	Shrubs
6	Hibiscus rosa-sinensis	*Hibiscus rosa-sinensis, HR*	Shrubs
7	Ficus ginseng	*Ficus microcarpa* 'Golden Leaves', FMGL	Shrubs
8	Monstera deliciosa	*Monstera deliciosa, MD*	Herbs
9	c	*Canna indica, CI*	Herbs
10	Nephrolepis	*Nephrolepis cordifolia, NC*	Herbs

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Table 1 shows the selected trees include Ficus microcarpa, Cinnamomum camphora, Bombax ceiba, and Delonix regia. Shrubs include Rhododendron simsii, Hibiscus rosa-sinensis, and Ficus microcarpa Golden Leaves. Herbaceous plants include Monstera deliciosa, Canna indica, and Nephrolepis cordifolia. The study selected 10 species encompassing trees, shrubs, and herbaceous plants to represent diverse ecological function types and resource utilization strategies. Selection criteria included their prevalence in urban landscapes, ecological functional diversity, and differential responses to various environmental stresses, thereby ensuring the sample's representativeness in terms of traits and adaptability.

Experimental materials and process design

At each sampling site, select three robust adult plants of each target species that are healthy and free of pests or diseases. Collect five fully expanded mature leaves from the sun-exposed mid-canopy region of each plant, totaling 15 leaves per species. During sampling, immediately place collected leaves into self-sealing bags and mark the sampling time, location, and plant species on-site. Samples are stored in sampling boxes and kept refrigerated before analysis. According to the LES concept, the study measures leaf morphological structure, physiological traits, and element contents. Leaf structural traits include Leaf Thickness (LT), Leaf Area (LA), Leaf Shape Index (LSI), Specific Leaf Area (SLA), Leaf Volume (LV), Leaf Tissue Density (LTD), Leaf Fresh Weight (LFW), Leaf Dry Weight (LDW), and Leaf Dry Matter Content (LDMC). The functions of these traits are listed in *Table 2*.

Table 2. *Leaf structural trait indicators*

Character	Unit	Ecological role
LT	mm	Reflect drought tolerance and water loss
LA	cm^2	Indicates photosynthetic capacity and environmental adaptation
LSI	/	Reflect photosynthetic efficiency
SLA	cm^2/g	Reflect resource acquisition strategies, growth rates
LV	cm^3	Reactive water and nutrient storage capacity
LTD	g/cm^3	Reflect resistance
LFW	g	Reflect to hydration status and metabolic vigor
LDW	g	Reflect resource acquisition and nutrient conservation capacity
LDMC	g/kg	Reflect resource competition and adaptive strategy

LT reflects plant drought resistance and water loss. It is measured with a high-precision caliper, avoiding the main vein, at three uniform points on the upper, middle, and lower leaf parts. The average of these values is the LT. LA and LSI reflect photosynthetic capacity. LA is obtained by scanning the leaf and importing the image into CAD software to get proportional Leaf Length (LL), Leaf Width (LW), and LA. The LSI calculation equation is shown in *Equation 1* (Mao et al., 2023).

$$LI = \frac{LL}{LW} \quad \text{(Eq.1)}$$

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LFW reflects plant hydration status and metabolic activity. Leaves are soaked in water and placed in a 5°C dark environment until saturated. After wiping off water and impurities, leaves are weighed with an electronic balance to get fresh weight. LDW reflects plant resource acquisition and nutrient storage. Leaves are dried in an oven until weight stabilizes; the constant weight is the LDW (Moccio et al., 2024). LDMC is calculated from LFW and LDW using *Equation 2* (Lamont and Lamont, 2025).

$$LDWC = \frac{LDW}{LFW} \qquad \text{(Eq.2)}$$

LV reflects water and nutrient storage capacity, calculated by *Equation 3* (Bruhn et al., 2024).

$$LV = LA \times LT \qquad \text{(Eq.3)}$$

LTD is an important indicator of plant stress resistance, calculated by *Equation 4* (Piña et al., 2024).

$$LTD = \frac{LDW}{LV} \qquad \text{(Eq.4)}$$

In addition to morphological traits, physiological traits and element contents are measured, as shown in *Table 3*.

***Table 3.** Leaf physiological traits and element content indicators*

Character	Unit	Ecological role
SPAD	/	Reflects the absorption, transfer and transformation of light energy by plants
Photosynthetic rate (Pr)	$\mu mol/m^2/s$	Reflects photosynthetic capacity
Transpiration rate (Tr)	$g/(m^2 \cdot h)$	Reflects the plant's ability to transpire water
Leaf carbon content (C)	g/kg	Cost of plant leaf tissue construction, related to plant growth and development
Leaf nitrogen content (N)	g/kg	Correlates with plant photosynthetic rate and reflects plant growth and development
Leaf carbon to nitrogen ratio (C:N)	/	Reflects plant growth rate

In *Table 3*, the study measures SPAD, Photosynthetic rate (Pr), and Transpiration rate (Tr). SPAD is measured by a portable chlorophyll meter (HM-YD) under clear and windless conditions between 9:00 and 11:00 AM. Six random points away from leaf veins on healthy, fully expanded mature leaves are measured. The average is the plant's SPAD value (Tripathi et al., 2024). Pr and Tr are measured in the same time frame using a portable photosynthesis system set to red and blue light at 1500 $\mu mol/(m^2/s)$. Mature leaves in the middle canopy are measured multiple times to ensure reliability; the average is the final result (Ravi et al., 2024; Li et al., 2023) Leaf carbon (C) and nitrogen (N) contents are measured by grinding oven-dried leaves to constant weight, followed by analysis using a carbon-nitrogen analyzer (Vario MAX Cube). The carbon-to-nitrogen ratio is then calculated (You et al., 2024; Xu et al., 2023).

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Results

Analysis of leaf functional traits in garden plants

Based on the LES theoretical framework, the study systematically measured and analyzed leaf functional traits of ten garden plants. After obtaining original data through experimental observation and field surveys, Excel 2010 was used for data organization and statistical analysis. The mean values of leaf functional trait parameters for each plant were calculated. The specific results are shown in *Table 4*.

Table 4. *Morphological leaf trait indicators of garden plants*

Plants	LT (mm)	LA (cm2)	LSI	SLA (cm2/g)	LV (cm3)	LTD (g/cm3)	LFW (g)	LDW (g)	LDMC (g/kg)
FM	0.30±0.03	22.75±2.18	1.98±0.05	110.25±11.12	0.72±0.06	0.22±0.02	0.84±0.24	0.21±0.03	321.24±25.24
CC	0.32±0.04	17.35±2.22	1.75±0.04	76.35±8.42	0.64±0.09	0.28±0.04	1.04±0.51	0.34±0.07	344.45±22.52
BC	0.21±0.02	75.50±8.31	2.82±0.12	144.27±17.74	1.62±0.12	0.15±0.02	1.84±0.25	0.51±0.05	272.27±20.27
DR	0.22±0.05	61.31±7.01	3.62±0.14	118.42±14.2	1.87±0.13	0.20±0.02	1.23±0.31	0.36±0.02	295.15±18.35
RS	0.36±0.05	10.52±1.55	1.43±0.06	66.68±6.24	0.47±0.06	0.35±0.03	0.67±0.19	0.18±0.01	376.27±14.45
HR	0.16±0.02	88.44±10.14	2.64±0.12	165.55±18.64	1.75±0.14	0.13±0.01	1.75±0.21	0.40±0.03	244.15±20.58
FMGL	0.25±0.03	28.11±3.25	1.91±0.06	121.15±14.74	1.04±0.12	0.10±0.01	1.57±0.15	0.31±0.04	291.28±21.41
MD	0.09±0.01	115.31±13.11	3.50±0.08	221.42±23.52	1.53±0.04	0.12±0.03	2.37±0.31	0.08±0.01	215.38±13.54
CI	0.14±0.01	224.21±25.24	4.95±0.09	187.85±21.37	2.74±0.05	0.13±0.02	3.15±0.26	1.10±0.03	244.45±11.75
NC	0.08±0.01	5.51±0.87	8.21±0.10	229.45±27.58	0.24±0.03	0.07±0.01	0.27±0.05	0.07±0.01	198.25±10.15

Table 4 showed significant differences in leaf characteristics among different plants. For LT, RS, CC, and FM all reached values above 0.30. CI, HR, MD, and NC exhibited typical fast-growing traits with SLA values of 187.85 cm^2/g, 165.55 cm^2/g, 221.42 cm^2/g, and 229.45 cm^2/g, respectively, all significantly higher than other plant types. In contrast, conservative plants like RS and CC had SLA values of only 66.68 cm^2/g and 76.35 cm^2/g. MD and NC showed high LSI and low LTD morphological traits; their LSI values were 3.50 and 8.21, and LTD values were 0.12 g/cm^3 and 0.07 g/cm^3, respectively. Regarding LV, CI had the highest LV at 2.74 cm^3, while NC had the lowest at 0.24 cm^3. All ten garden plants had dry matter content above 150 g/kg, with NC having the lowest LDMC at 198.25 g/kg, and RS having the highest LDMC at 376.27 g/kg. CC and FM followed with LDMC values of 321.24 g/kg and 344.45 g/kg. Beyond morphological traits, physiological traits and element content statistics are shown in *Figure 4*.

As shown in *Figure 4*, noticeable differences were observed among the ten garden plant species in terms of their leaf physiological traits and elemental content. *Figure 4a* illustrated that CI exhibited the highest SPAD value, reaching 3.5, followed by HR and CC. In contrast, NC had the lowest SPAD reading, with a value of only 1.1, indicating relatively lower chlorophyll content and photosynthetic potential. According to *Figure 4b*, CI again demonstrated the most favorable performance in net Pr, maintaining the highest value among all species. Meanwhile, RS, MD, and NC exhibited relatively low Pr values, all below 8.0 μmol/(m^2/s), suggesting a lower carbon assimilation efficiency in these species. In *Figure 4c*, Tr of CI was the highest, reaching 11.0 g/($m^2 \cdot h$). This was followed by HR and BC, which also displayed relatively high Tr values. On the other hand, NC recorded the lowest transpiration rate, with a value of only 2.5 mmol/($m^2 \cdot h$), indicating a comparatively conservative water use strategy. *Figure 4d* and *e* presented the elemental composition of the leaves. RS had the highest C content, reaching 550 g/kg, which was significantly greater than that of the other species.

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However, its N content was only 16 g/kg, placing it in the lower-middle range among all sampled plants. NC consistently showed the lowest elemental values, with its C and N contents being only 350 g/kg and 12 g/kg, respectively. In *Figure 4f*, the C:N ratio of RS reached a maximum of 45, significantly exceeding the values recorded in other species. MD and NC also showed relatively high C:N ratios, indicating a resource-conserving strategy. In contrast, CI had the lowest C:N ratio, measured at only 14, which suggested a more active investment in nitrogen-related functions such as photosynthesis and protein synthesis. Following the assessment of physiological and chemical traits, a statistical analysis of variance (ANOVA) was conducted to evaluate differences in leaf structural traits among the ten species. The results of this analysis are presented in *Table 5*.

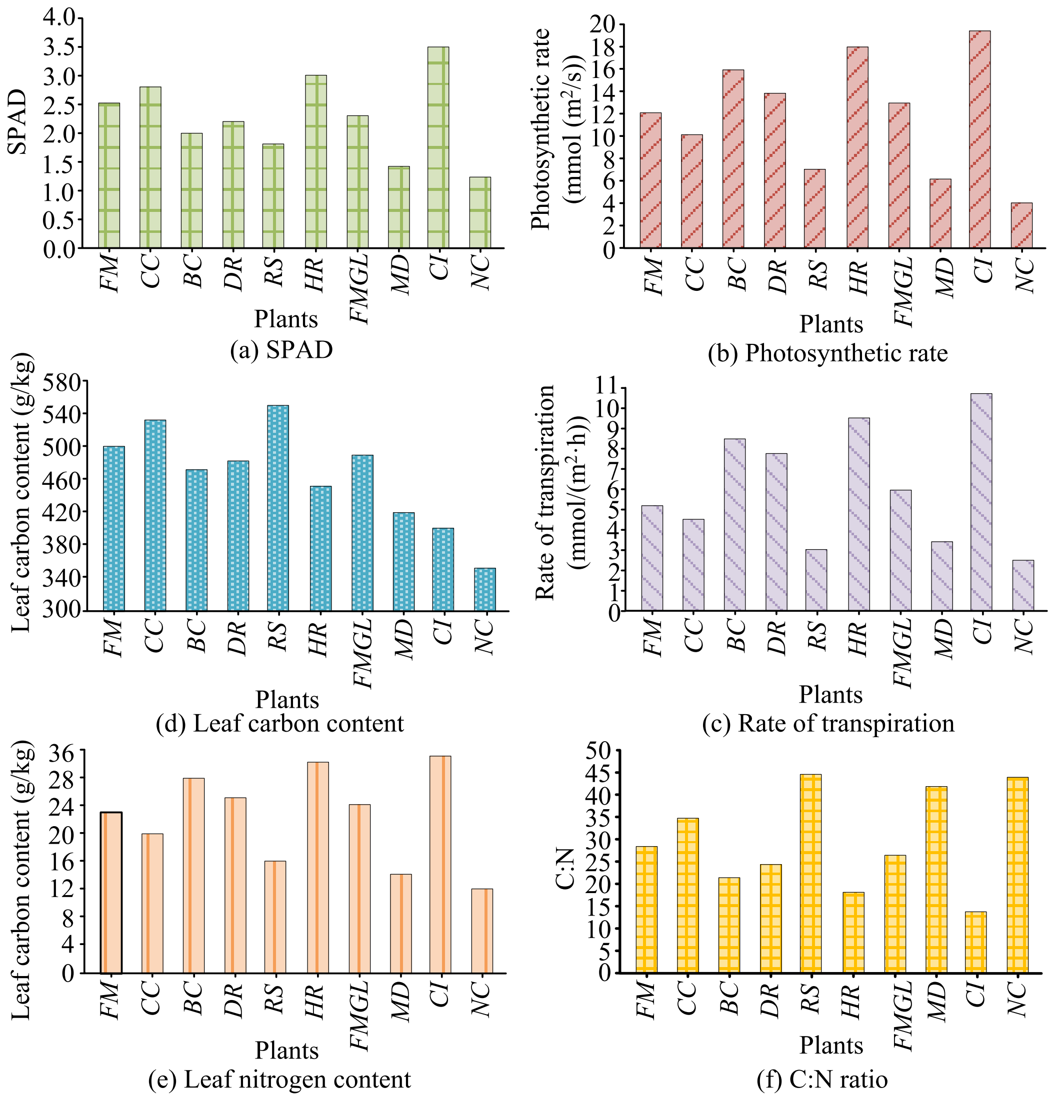

***Figure 4.** Physiological leaf traits and element contents of garden plants*

Table 5 showed that all nine leaf morphological traits exhibited extremely significant differences among the ten garden plants with p-values less than 0.001. According to the F-values, LA (F=112.45) and LV (F=94.51) had the most significant between-group differences, indicating the largest variation among species for these traits. Following were

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LFW (F=78.34), SLA (F=76.83), and LDW (F=65.42), which also showed high interspecies variability. LT (F=58.37) and LTD (F=63.19) had slightly lower but still extremely significant F-values. LDMC had the smallest F-value of 47.25 but maintained a p-value below 0.001, indicating significant differences among plants. In addition, one-way ANOVA of physiological traits and element contents was performed, with results shown in *Table 6*.

Table 5. *One-way ANOVA of leaf structural traits*

Morphological trait index	SS	df	MS	F	*p*
LT	1.52	9	0.17	58.37	<0.001***
LA	28560.27	9	3173.42	112.45	<0.001***
LSI	89.26	9	9.92	89.26	<0.001***
SLA	8420.54	9	935.61	76.83	<0.001***
LV	12.45	9	1.38	94.51	<0.001***
LTD	0.428	9	0.05	63.19	<0.001***
LFW	35.82	9	3.98	78.34	<0.001***
LDW	1.87	9	0.21	65.42	<0.001***
LDMC	125600.27	9	13955.65	47.25	<0.001***

** indicates $p<0.01$; * indicates $p<0.05$

Table 6. *One-way ANOVA of physiological traits and element contents*

Physical traits indicators	SS	df	MS	F	*p*
SPAD	15.32	9	1.70	62.45	<0.001***
Pr	680.25	9	75.62	98.23	<0.001***
Tr	210.44	9	23.65	84.67	<0.001***
C	42500.71	9	4722.63	53.18	<0.001***
N	380.55	9	42.34	75.63	<0.001***
C:N	2850.24	9	316.76	48.92	<0.001***

Table 6 revealed that the six key physiological traits showed extremely significant differences ($p < 0.001$) among the ten garden plants. Regarding SS, carbon content had the largest total variation at 42500.71, with MS reaching 4722.63. Although Pr had a relatively small total variation (SS = 680.25), it showed the highest F-value with between-group mean square and within-group variation ratios at 75.62 and 98.23, respectively. Tr and nitrogen content showed relatively small total variations but had high F-values of 84.67 and 75.63, indicating considerable within-group variation. The C:N ratio had the lowest F-value of 48.92, but both total variation and between-group variation were relatively high at 2850.24 and 316.76, respectively.

Correlation analysis of leaf functional traits and ecological adaptability in garden plants

During plant adaptation to the environment, leaf morphology and physiological traits formed specific functional combinations, reflecting coordination mechanisms among water use, stress resistance, and photosynthetic efficiency in ecological conditions.

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Therefore, after completing descriptive and variance analyses of leaf functional traits, the study applied multidimensional statistical methods to systematically evaluate the ecological adaptability of ten garden plants. Pearson correlation analysis and Principal Component Analysis (PCA) were further used to establish a quantitative evaluation system, providing data support for ecological adaptability assessment. The study first explored correlation patterns among leaf structural traits through Pearson correlation analysis, with specific results shown in *Table 7*.

Table 7. *Correlation coefficients among leaf structural traits*

Morphological trait index	LT	LA	LSI	SLA	LV	LTD	LFW	LDW	LDMC
LT	1	\	\	\	\	\	\	\	\
LA	-0.68*	1	\	\	\	\	\	\	\
LSI	-0.72*	0.48*	1	\	\	\	\	\	\
SLA	-0.89**	0.82**	0.59*	1	\	\	\	\	\
LV	-0.54*	0.95**	0.52*	0.78*	1	\	\	\	\
LTD	0.91**	0.76*	-0.65*	-0.94**	-0.72*	1	\	\	\
LFW	-0.62*	0.93**	0.55*	0.85**	0.97**	-0.80**	1	\	\
LDW	-0.45*	0.88**	0.41*	0.81**	0.90**	-0.68*	0.95**	1	\
LDWC	0.85**	-0.79*	-0.71*	-0.92**	-0.74*	0.87**	-0.83**	-0.77*	1

Table 7 indicates that significant correlations exist among various leaf structural traits. The correlation coefficient between LT and LTD is 0.91, revealing a highly significant positive relationship, which confirms the synergistic growth of leaf size and weight. LA exhibits highly significant positive correlations with LV and LFW, while its correlation coefficient with LSI is the smallest at only 0.48. LSI shows a significant negative correlation with LDWC at the 0.05 level, with a correlation coefficient of -0.71. Leaf specific area demonstrates highly significant positive correlations with LTD and LDWC, both with correlation coefficients exceeding 0.9. LV showed extremely significant positive correlations with both LFW and LDW, with the correlation coefficient reaching 0.97 for LFW. This indicates that leaf weight is primarily determined by leaf volume, while leaf water content is a key factor influencing the relationship between fresh weight and dry weight. Subsequent studies analyzed the correlations among physiological traits and elemental content in ornamental plant leaves, with results presented in *Figure 5*.

As shown in *Figure 5*, SPAD values exhibited significant positive correlations with both Pr and N content, with correlation coefficients exceeding 0.8. This indicates that leaf nitrogen levels and chlorophyll content jointly promote photosynthetic activity. Pr showed significant positive correlations with Tr and N content, while exhibiting a significant negative correlation with C:N. Notably, the correlation coefficient between Pr and Tr reached 0.92, demonstrating a close coupling between water use and carbon assimilation processes. The correlation coefficient between Tr and N content was 0.79, indicating a significant positive relationship; Tr also showed a significant negative correlation with C:N, further confirming nitrogen's crucial role in enhancing leaf photosynthetic and transpiration efficiency. A resource trade-off phenomenon existed between C and N content, with a negative correlation coefficient of -0.65. The study further calculated correlation coefficients between leaf morphological structure, physiological traits, and elemental content, with the resulting structure shown in *Table 8*.

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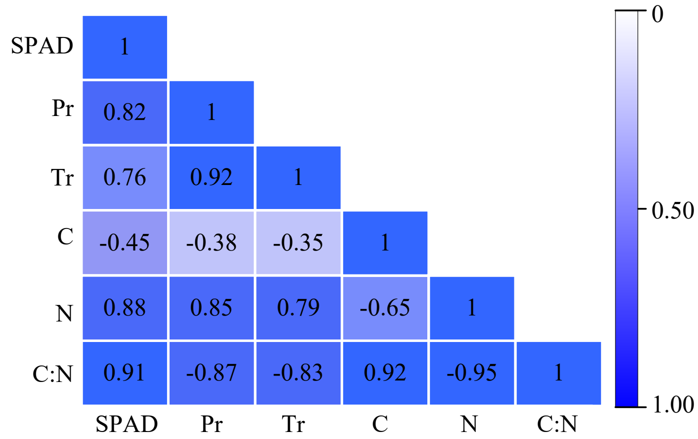

Figure 5. *Correlation coefficients among physiological traits and element contents*

Table 8. *Correlation coefficients between leaf morphology and physiological traits*

Leaf functional traits	SPAD	Pr	Tr	C	N	C:N
LT	-0.52*	-0.65**	-0.58*	0.72**	-0.68**	0.81**
LA	0.78**	0.84**	0.79**	-0.61**	0.82**	-0.76**
LSI	0.34	0.41*	0.38*	-0.47*	0.39*	-0.52*
SLA	0.85**	0.88**	0.83**	-0.77**	0.90**	-0.87**
LV	0.76**	0.81**	0.77**	-0.59**	0.80**	-0.73**
LTD	-0.73**	-0.79**	-0.75**	0.84**	-0.80**	0.88**
LFW	0.74**	0.80**	0.76**	-0.57**	0.78**	-0.71**
LDW	0.63**	0.70**	0.67**	-0.48	0.69**	-0.61**
LDMC	-0.81**	-0.86**	-0.83**	0.78**	-0.85**	0.91**

Table 8 shows that the correlation coefficient between LT and C:N reached 0.81, indicating a highly significant positive correlation at the 0.01 level. This suggests that thicker leaves are often associated with a conservative resource investment strategy. LA exhibited a highly significant positive correlation with Pr and N content. The correlation coefficient between LSI and C:N is -0.52, indicating a significant but moderate relationship. SLA shows significant positive correlations with SPAD, Pr, Tr, and N content, with the strongest correlation observed for N content. This suggests plants efficiently allocate nitrogen resources by constructing higher SLA to maximize returns on photosynthetic capacity. LA and LTD showed significant correlations with all six physiological traits and elemental contents. The relatively weak correlation between LA and C content suggests potential regulation by other factors. LDWC exhibited significant negative correlations with SPAD, Pr, Tr, and N content, while showing a significant positive correlation with C:N. Subsequent research conducted principal component analysis (PCA) on horticultural plant traits to extract key shapes of dominant ecological adaptability from multiple correlated traits, providing quantitative evidence for assessing ecological adaptability. Before applying PCA, the study examined the statistical foundation to ensure data suitability. Sufficient linear correlation among variables was verified through Bartlett's sphericity test and KMO measures. Subsequently, the scree plot and loading vectors derived from PCA are presented in *Figure 6*.

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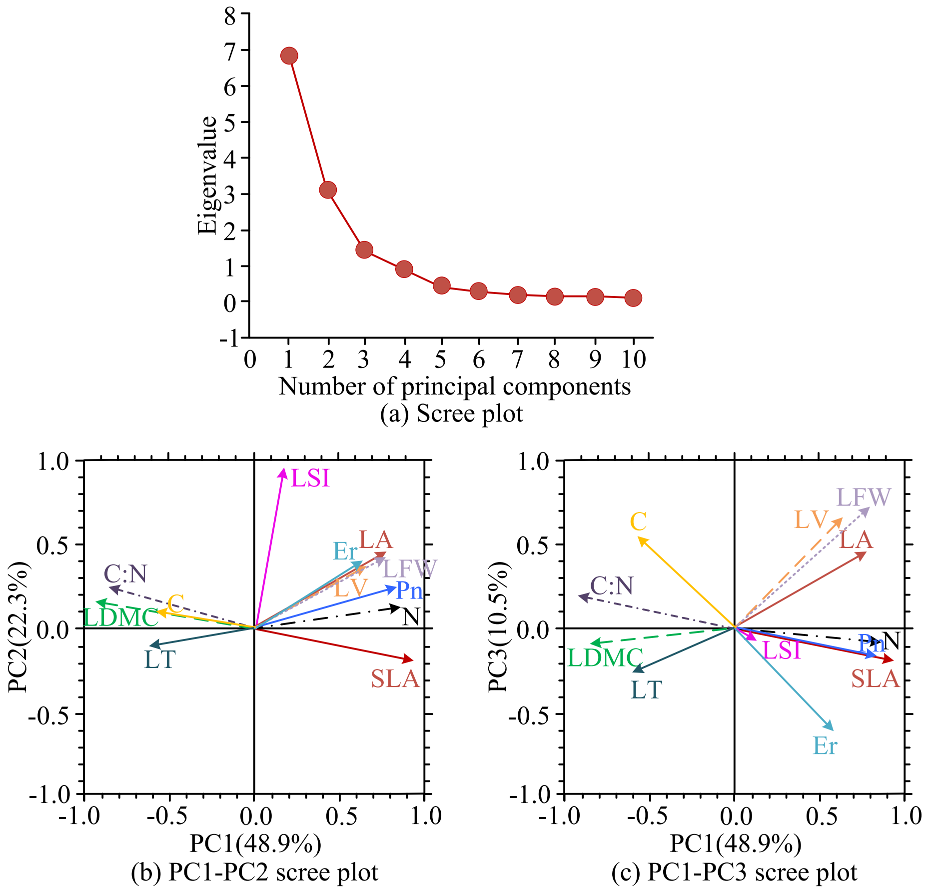

Figure 6. *PCA of garden plant functional traits*

As shown in *Figure 6a*, the eigenvalues decrease progressively with increasing principal component number. Beyond the fourth principal component, the curve flattens, indicating that the initial principal components capture most of the trait information. The eigenvalues are 6.85 for PC1, 3.12 for PC2, and 1.42 for PC3. Following the principle of retaining only principal components with eigenvalues greater than 1, three principal components were retained for analysis. As shown in *Figures 6b* and *c*, PC1 explains 48.9% of the variance, PC2 explains 22.3%, and PC3 explains 1.05%. The first two principal components collectively explain 71.2% of the total variance. In *Figure 6b*, most trait vectors are long and concentrated in the first quadrant, indicating strong positive correlations with both PC1 and PC2. The three trait indices LDMC, C content, and C:N are located at the negative end of PC1 and the positive end of PC2. Among these, LDMC exhibits a clear inverse relationship with SLA, which represents a rapid resource recycling strategy. This reveals a trade-off between “conservative” and “acquisition-oriented” strategies in the leaf economic spectrum. As shown in *Figure 6c*, LFW and LV have the longest lengths, indicating their highest representativeness in the defined principal component space. LSI exhibited the shortest length, indicating its relatively limited contribution to the overall trait pattern. Principal component analysis identified six key principal components: SLA, N content, Pn, LFW, Tr, and LDMC. To unify these traits with ecological indicators, the study employed fuzzy membership function methods for standardization calculations. Raw observational values for each trait were converted into membership values between “0” and “1” to quantitatively represent the strength of

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plant environmental adaptability. where “1” indicates the strongest environmental adaptation capacity. Finally, by calculating the average membership degree of all key traits for each species, a functional value representing its comprehensive adaptation capacity was obtained. The membership function values and average membership values for key traits of the ten garden plants are shown in *Figure 7*.

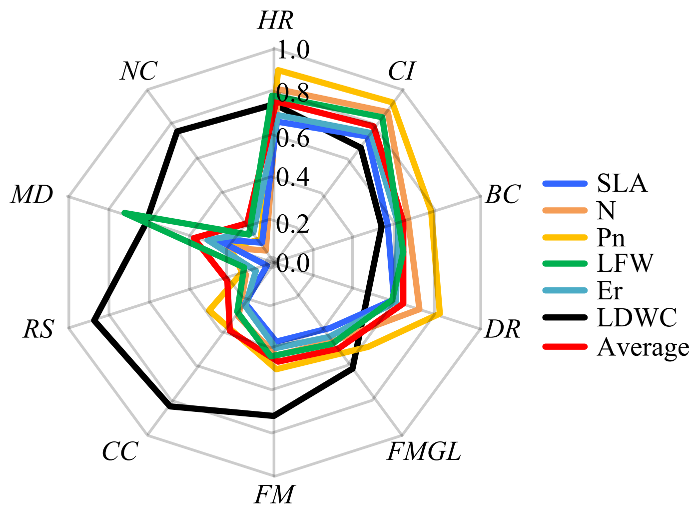

Figure 7. *Membership function values and averages for key traits of garden plants*

As shown in *Figure 7*, the membership function values of the 10 different landscape plants exhibit significant differences, allowing them to be classified into three adaptation levels-high, medium, and low-based on their overall performance. BC and CI achieved membership function values of 0.76 and 0.78, respectively, demonstrating the highest ecological adaptability. This is primarily attributed to their outstanding performance in key functions such as photosynthesis, nitrogen utilization, and biomass accumulation. DR and BC exhibited relatively balanced membership function values across all indicators, with their average membership function ranking second only to BC. FMGL, FM, and MD all demonstrated moderate ecological adaptability. While MD showed advantages in biomass accumulation, its performance was constrained by relatively low photosynthetic efficiency. LFW exhibited relatively prominent membership function values, yet its photosynthetic efficiency was weak, with a membership function value of only 0.22. The average membership function values for CC, RS, and NC were 0.38, 0.24, and 0.23 respectively, indicating lower adaptability scores. However, these three plants excelled in LDWC, with membership functions reaching 0.82, 0.88, and 0.75 respectively. This indicates their potential adaptive advantage under drought stress conditions. Among them, RS exhibits a typical “conservative” survival strategy, investing less in most functional traits while maintaining high stress resistance.

Discussion

The study systematically analyzed the functional traits of urban landscape plant leaves, revealing that their ecological strategies significantly align with the theoretical framework of the leaf economic spectrum. Specifically, specific leaf area (SLA), representing rapid resource return, showed a significant negative correlation with leaf dry weight per

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centimeter of stem (LDWC), reflecting conservative investment, while exhibiting a positive correlation with nitrogen content. Fast-growing plants exhibited significantly higher specific leaf area than other plant types, whereas conservative plants possessed higher fresh leaf weight and dry leaf weight. Matsuo et al. (2024) measured leaf functional traits across diverse plant species, revealing significant regional variations in leaf characteristics and demonstrating that herbaceous plants and trees fundamentally employ distinct ecological adaptation strategies. In a study based on the leaf economics spectrum, Helsen et al. (2023) measured 97 leaf functional trait indices in terrestrial and fern plants from Taiwan's tropical forests, finding significant trait differences among species, with ferns exhibiting markedly lower leaf area and nitrogen content compared to terrestrial plants. Further supporting these patterns, Islam et al. (2024) measured functional traits including leaf thickness and leaf dry matter content across an elevation gradient in mountainous regions, observing that woody plants showed significantly higher leaf thickness and dry matter content than herbaceous plants, with correlation analyses revealing consistent negative relationships between leaf area and other leaf traits. These findings corroborate the classic studies, further confirming that interspecific variation in plant functional traits is a universal phenomenon across ecosystems. They also demonstrate that the investment-return patterns revealed by the leaf economic spectrum exhibit remarkable universality, whether in tropical forests, alpine ecosystems, or urban landscaping environments.

However, compared to wild plant communities, landscape plants exhibit unique distribution patterns on the leaf economic spectrum. Research indicates that species with higher adaptability tend to favor rapid-return strategies, differing from patterns observed in natural ecosystems. This divergence primarily stems from the influence of artificial selection in landscaping. During urbanization, landscaping employs directed breeding and plant combinations to achieve rapid visual impact and ornamental goals. Concurrently, standardized maintenance practices gradually erode species' adaptive capabilities developed in wild environments, diminishing their competitive advantages. Fares and Michelan (2024) measured leaf traits including leaf area and leaf dry matter content, revealing significant interspecific variation in leaf characteristics and demonstrating how environmental factors shape trait variation among species. In a complementary grassland experiment, Pichon et al. (2024) investigated the relationship between nitrogen availability and plant functional diversity through the lens of the leaf economics spectrum. Their analysis of functional relationships demonstrated that rapid species turnover enhances functional effects, though this relationship is modulated by both nitrogen enrichment and predator pressure. These findings provide a theoretical foundation for understanding how nutrients influence plant survival strategies in urban environments. They also demonstrate that the trait combinations observed in landscape plants represent unique adaptive patterns shaped by both natural selection and human-directed selection. O'Sullivan et al. (2022) analyzed eight leaf functional traits and, through PCA, found high variability (20%-44%) among species traits, confirming substantial ecological variation within individual species. These findings collectively indicate that plant adaptability must fully account for habitat specificity.

Furthermore, based on the leaf economic spectrum framework, researchers extracted key traits through PCA and employed membership functions for adaptive evaluation. Avalos et al. (2023) investigated palm ecological strategies by first analyzing functional traits through the leaf economic spectrum. They then derived a correlation matrix of morphological traits via Pearson correlation analysis. Following PCA, four key components were extracted, and resource utilization and acquisition strategies were

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analyzed to elucidate palm ecological adaptability. Zhang et al. (2023) investigated adaptive strategies of Asian basin desert plants along environmental gradients by measuring 13 leaf economic traits. PCA results showed that key components on the first and second axes explained 99.99% of trait variation. This demonstrates that the methods employed in this study corroborate those used in previous research. The established adaptation evaluation system based on key principal component traits not only validated the applicability of the leaf economic spectrum in urban ecosystems but more importantly revealed the unique adaptive mechanisms formed by ornamental plants through long-term artificial domestication.

Finally, the study recommends prioritizing nitrogen-utilizing species with high photosynthetic efficiency during plant selection. These plants combine high photosynthetic rates with strong nitrogen utilization capabilities, enabling rapid landscape formation and adaptation to urban environmental stresses. Concurrently, drought-tolerant species should be strategically integrated to enhance the ecological resilience of plant communities through their superior drought and nutrient-poor soil tolerance. For maintenance, differentiated care should be implemented based on plant type. Fast-growing species require adequate water and fertilizer supply, while conservative species should receive reduced irrigation to optimize resource allocation. Landscape planning should adopt functionally complementary mixed planting schemes, scientifically combining rapidly growing ornamental plants with highly stress-tolerant conservation plants. This approach ensures aesthetic appeal while enhancing community stability.

Conclusion

Garden plants played a crucial role in improving urban environments and maintaining biodiversity. This study aimed to reveal leaf functional traits and ecological adaptability of garden plants. After measuring leaf functional traits of 10 garden plant species, Pearson correlation analysis showed a strong negative correlation between SLA and LDMC, and a significant positive correlation between SLA and nitrogen content. PCA and fuzzy membership function analysis indicated that Hibiscus HR and CI exhibited higher ecological adaptability. FMGL, FM, and MD showed moderate adaptability. RS and NC displayed the weakest adaptability among the studied species. Due to experimental limitations, this study focused only on common garden species in a specific region. Future research should expand species and geographic coverage to improve the generalizability of the findings.

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