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Photosynthetic pigment profiles of climbing plants for green wall applications in semi-arid urban areas: A case study in Van, Türkiye*

Yarı-kurak kentsel alanlarda yeşil duvar uygulamaları için tırmanıcı bitkilerin fotosentetik pigment profilleri: Van, Türkiye örneği

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ABSTRACT

Objective: This study aimed to evaluate the photosynthetic pigment profiles of climbing and creeping plant species commonly used in the semi-arid urban landscape of Van, Türkiye. The objective was to assess their physiological performance and determine their suitability for green infrastructure and vertical greening applications.

Material and Methods: Chlorophyll a (Chl a), chlorophyll b (Chl b), and Chl a/b ratios were determined using three different spectrophotometric approaches. The obtained data were statistically compared, and species were classified according to their pigment characteristics using Principal Component Analysis (PCA) and hierarchical clustering.

Results: Absolute pigment values varied among analytical methods, but overall trends were consistent. The Chl a/b ratio differed significantly among methods (p<0.001). *Solanum crispum* and *Rubia tinctorum* showed the highest total chlorophyll contents (up to 54.09 mg g^{-1} FW), whereas *Campsis radicans* and *Lonicera japonica* had lower pigment levels (<20 mg g^{-1} FW). PCA and hierarchical clustering clearly separated species based on pigment composition.

Conclusion: Chlorophyll content and Chl a/b ratios serve as reliable indicators of light adaptation and photosynthetic efficiency in climbing plants. Incorporating these traits into species selection for vertical greening can enhance ecological resilience and ecosystem services in semi-arid urban environments.

Keywords: Chlorophyll, climbers, landscape, pigments, urban

ÖZ

Amaç: Bu çalışma, yarı kurak iklim koşullarına sahip Van kentinde yaygın olarak kullanılan tırmanıcı ve sürünücü bitki türlerinin fotosentetik pigment profillerini değerlendirmeyi amaçlamıştır. Çalışmanın amacı, bu türlerin fizyolojik performanslarını belirlemek ve yeşil altyapı ile dikey yeşillendirme uygulamalarına uygunluklarını ortaya koymaktır.

Materyal ve Yöntem: Klorofil a (Chl a), klorofil b (Chl b) ve Chl a/b oranları üç farklı spektrofotometrik yöntem kullanılarak analiz edilmiştir. Elde edilen veriler istatistiksel olarak karşılaştırılmış, Temel Bileşen Analizi (PCA) ve hiyerarşik kümeleme yöntemleriyle türlerin pigment özelliklerine göre sınıflandırılması yapılmıştır.

Araştırma Bulguları: Mutlak pigment değerleri kullanılan analitik yöntemlere göre değişmekle birlikte genel eğilimler benzer bulunmuştur. Chl a/b oranı yöntemler arasında anlamlı farklılık göstermiştir (p<0.001). *Solanum crispum* ve *Rubia tinctorum* en yüksek toplam klorofil içeriklerini göstermiştir (en fazla 54.09 mg g^{-1} FW), buna karşılık *Campsis radicans* ve *Lonicera japonica* daha düşük pigment düzeylerine (<20 mg g^{-1} FW) sahip olmuştur. PCA ve hiyerarşik kümeleme analizleri türleri pigment bileşimlerine göre açık şekilde ayırmıştır.

Sonuç: Klorofil içeriği ve Chl a/b oranı, tırmanıcı bitkilerde ışık adaptasyonu ve fotosentetik etkinliğin güvenilir göstergeleridir. Bu özelliklerin dikey yeşillendirme tür seçimine entegre edilmesi, ekolojik dayanıklılığı ve kentsel ekosistem hizmetlerini artırabilir.

Anahtar sözcükler: Klorofil, sarılıcılar, peyzaj, pigmentler, kentsel

INTRODUCTION

Rapidly increasing urbanization in developing countries is leading to significant transformations in the natural environment. This transformation is not limited to the decline of green spaces; it also brings about multidimensional environmental problems such as deterioration of air quality, weakening of ecosystem services, and urban microclimate imbalances (Pörtner et al., 2022). In this context, integrating nature-based solutions into urban planning processes plays a critical role in achieving sustainable urbanization goals. The use of vertical surfaces as green infrastructure elements, especially in dense urban centers with limited surface areas, has become increasingly important in recent years (Manso & Castro-Gomes, 2015).

Climbing and creeping plants used in vertical green systems are gaining prominence in sustainable landscaping practices thanks to their low maintenance requirements, high adaptability, and versatile environmental contributions (Perini & Ottelé, 2014). These plants provide thermal insulation by filtering sunlight on structural surfaces, reduce the urban heat island effect through evaporative cooling, and improve air quality by sequestering atmospheric carbon (Pérez et al., 2011; Morakinyo et al., 2017). At the core of these contributions lies photosynthetic capacity, where photosynthesis is the fundamental biochemical process by which atmospheric carbon dioxide is converted into organic compounds. Furthermore, plants in urban environments, including those used in vertical greening systems, contribute not only to ecological functions but also to social and aesthetic values. Vegetation in urban streets, parks, and public spaces enhances the livability of cities by providing shade, reducing the flow of stormwater, and improving air quality (Mullaney et al., 2015; Taşçıoğlu, 2025). In addition, the presence of plants offers visual diversity through variations in form, texture, and color, which can positively influence human perception and well-being (Yılmaz et al., 2018). By integrating climbing plants into vertical surfaces, urban planners can transform otherwise hard, lifeless structures into visually appealing and environmentally functional components of the city, creating a more natural and human-oriented urban environment (Acar et al., 2010; Taşçıoğlu, 2025).

Chlorophyll pigments, central to the photosynthetic process, play a decisive role in the absorption of light energy and its conversion into chemical energy (Shafiq et al., 2021). Chlorophyll levels not only influence light-related metabolic processes; they also reflect ecologically critical parameters such as the plant's growth rate, tolerance to environmental stresses, and carbon sequestration capacity (Niinemets, 2004; Papageorgiou et al., 2007). Therefore, determining chlorophyll amounts is both a physiological indicator and an important criterion for predicting ecosystem services (Nowak et al., 2006; Escobedo et al., 2011).

Species with high chlorophyll content reduce ambient temperature through evapotranspiration and shading, thus reducing the urban heat island effect and increasing the energy efficiency of the building envelope (Bowler et al., 2010; Pérez et al., 2011). Therefore, selecting species for green facades based on their photosynthetic performance has the potential to strengthen the functional sustainability of urban landscapes (Perini & Ottelé, 2014; Morakinyo et al., 2017). Spectrophotometric methods commonly used for chlorophyll determination are based on the absorption measurements of plant tissue extracts prepared with specific solvents at different wavelengths. Among these methods, the classical 80% acetone-based protocol of Arnon (1949), the ethanol-based method of Lichtenthaler & Wellburn (1983), and the HPLC-assisted methanol-based approach of Porra (2002) stand out. These protocols differ in solvent structure, wavelengths, and calculation formulas, which can lead to variable results in the same samples (VanWoert et al., 2005; Sailor & Hagos, 2011). The primary objective of this study was to comparatively measure chlorophyll a, chlorophyll b, and total chlorophyll contents in leaf tissues of climbing and creeping ornamental plants commonly used in Van province using three different spectrophotometric methods (Arnon, Lichtenthaler & Wellburn, Porra) and to assess the statistical significance of the differences between the methods. The findings provide reliable data on the physiological resistance of these species and contribute to the literature by providing a comparative assessment of the consistency and selectivity of the analysis methods used. Determining the photosynthetic performance of species used in the greening of vertical surfaces in the semiarid city of Van is of strategic importance not only for landscape architecture applications but also for urban sustainability goals such as microclimatic regulation, energy efficiency, and carbon footprint reduction (Manso & Castro-Gomes, 2015; Akther et al., 2018).

In this context, the study sought to answer the following research questions:

Do three different spectrophotometric methods produce statistically significant differences in chlorophyll values measured on the same plant samples?

Can selected climbing and creeping ornamental plants be compared in terms of physiological resistance based on their chlorophyll levels?

Is there significant overlap between the methods in terms of measurement reliability and biological consistency?

MATERIALS and METHODS

Plant material

In this study, plant material was collected in 2024 from urban areas of Van city (Türkiye). Climbing and creeping plant species commonly used in the urban landscape of Van, a city characterized by a semi-arid climate, were selected for the study. The species were systematically characterized based on their morphological traits and evaluated for their potential use in urban landscape applications. Plant species were identified using standard botanical references (Table 1). When precise identification at the species or cultivar level was not possible, the plants were recorded at the genus level using the abbreviation spp.

Table 1. The species used as material in the study

Çizelge 1. *Çalışmada materyal olarak kullanılan türler*

Families	Scientific Names
1. Vitaceae	*Parthenocissus quinquefolia* (L.) Planch.
	Parthenocissus tricuspidata (Siebold & Zucc.) Planch.
2. Polygonaceae	*Fallopia baldschuanica* (Regel) Holub
3. Caprifoliaceae	*Lonicera japonica* Thunb
	Lonicera periclymenum L.
4. Bignoniaceae	*Campsis radicans* (L.) Seem.
5. Solanaceae	*Solanum crispum* Ruiz & Pav.
6. Fabaceae	*Wisteria sinensis* (Sims) Sweet
7. Rubiaceae	*Rubia tinctorum* L.

Methods

Plant samples were collected during the active vegetative growth period after full leaf development. Fully expanded and physiologically mature leaves were selected from healthy plants to minimize the potential effects of phenological variation on chlorophyll measurements

Pigment analyses

Fresh leaf samples from each plant species were weighed at 0.2 g (200 mg), crushed in a mortar, and homogenized. The homogenized leaf tissue was extracted with a solvent specific to the method. The resulting extracts were separated from the plant residue by centrifugation at 4000 rpm for 15 minutes at 4°C. The clear solution from the supernatant was used for spectrophotometric measurements.

Following the common preparation step, three different spectrophotometric methods were applied:

1. Arnon (1949) method: 80% acetone was used as the solvent, and absorbance values were measured at wavelengths of 645 nm and 663 nm. Chlorophyll a (mg/L) was calculated using the formula 12.7 × A663 – 2.69 × A645, and chlorophyll b (mg/L) was calculated using the formula 22.9 × A645 – 4.68 × A663. Total chlorophyll content was determined as the sum of these two values.

2. Lichtenthaler & Wellburn (1983) method: 96% ethanol was used as the solvent, and absorbance values were recorded at wavelengths of 470 nm, 645 nm, and 662 nm. Chlorophyll a (µg/ml) was calculated using the formula 13.36 × A662 – 5.19 × A645. Chlorophyll b (µg/ml) content was calculated using the formula 27.43 × A645 – 8.12 × A662. Total chlorophyll value was determined as the sum of these two parameters, and carotenoid contents were calculated using the formula 1000 × A470 – 2.13 × Chl a – 97.64 × Chl b.

3. Porra (2002) method: 100% methanol was used as the solvent, and measurements were made at wavelengths of 470 nm, 652 nm, and 665 nm. Chlorophyll a (µg/ml) was calculated using the formula 16.29 × A665 – 8.54 × A652, and chlorophyll b (µg/ml) was calculated using the formula 30.66 × A652 – 13.58 × A665. Total chlorophyll amount was determined as the sum of chlorophyll a and b values, and carotenoid contents were determined using the formulas suggested by Porra.

All samples were prepared in triplicate, and absorbance values were recorded using a spectrophotometer. Descriptive statistics (mean ± standard deviation) were calculated for chlorophyll a, chlorophyll b, and total chlorophyll and Chl a/b ratios for each species (µg/ml) using these methods.

Statistical analyses

One-way analysis of variance (One-Way ANOVA) was performed using the Python programming language to compare the measurement results of three different spectrophotometric methods. All statistical analyses were conducted using the Python libraries Pandas, NumPy, and SciPy. The significance level was set at 5% ($p<0.05$) in all analyses. Before performing ANOVA, the assumptions of normality and homogeneity of variances were tested using the Shapiro–Wilk test and Levene's test, respectively. The ANOVA test was performed to assess the presence of statistically significant differences between the methods in terms of chlorophyll a, chlorophyll b, and total chlorophyll values.

RESULTS

Chlorophyll a values

When chlorophyll a (Chl a) values obtained using three different spectrophotometric methods were compared, the Arnon (1949) method generally produced the highest estimates across most species, followed by the Lichtenthaler & Wellburn (1983) and Porra (2002) methods. However, one-way ANOVA indicated that the differences among methods were not statistically significant ($F=0.76$; $p=0.479$) (Figure 1). This result shows that, although slight numerical differences were observed among the methods, these differences were not strong enough to indicate a statistically meaningful methodological effect. Therefore, the three spectrophotometric approaches may be considered broadly comparable for Chl a determination under the present dataset, and the variation among methods appears to reflect minor methodological sensitivity rather than a consistent analytical bias.

In terms of interspecific variation, *S. crispum* exhibited the highest Chl a content by a clear margin, regardless of method, indicating a markedly greater pigment accumulation compared with the other species. *R. tinctorum* also showed relatively high Chl a value, while *P. tricuspidata, F. baldschuanica*, and *L. periclymenum* formed an intermediate group with moderate pigment levels. In contrast, *C. radicans, L. japonica, P. quinquefolia*, and *W. sinensis* displayed comparatively lower Chl a concentration (Figure 1). This distribution suggests that Chl a content is strongly species-dependent and may reflect differences in photosynthetic capacity, leaf pigmentation characteristics, and physiological adaptation among the studied climbing plants.

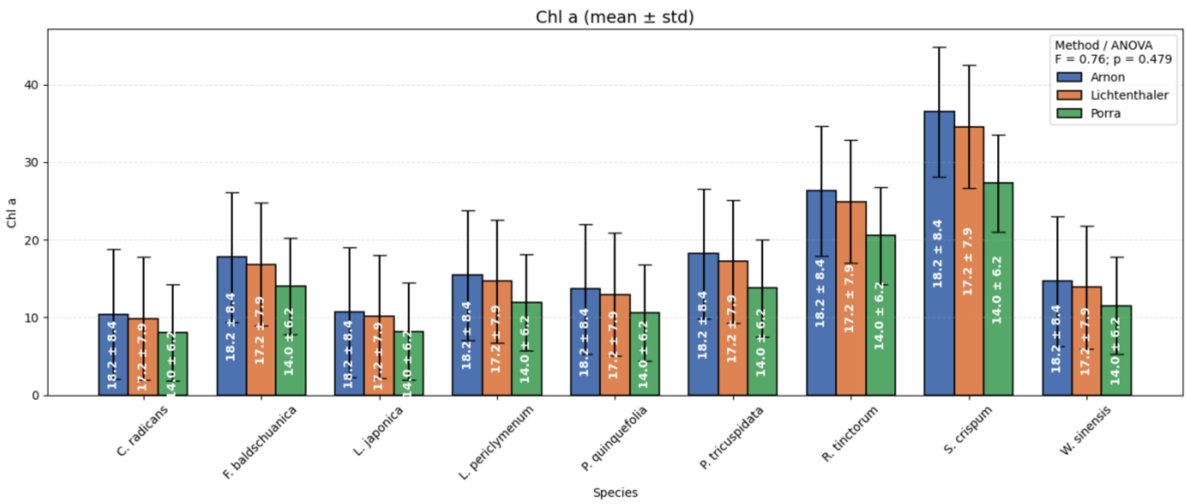

Figure 1. Chlorophyll a value of the studied species.
Şekil 1. *Türlere ait klorofil a değerleri.*

Although the general ranking pattern was largely consistent across methods, the absolute values differed slightly. Such variation may be associated with differences in extinction coefficients, solvent-specific optical behavior, extraction performance, and wavelength-based calculation procedures used by each method. Thus, while the overall biological interpretation remains stable, absolute Chl a value should still be interpreted with some caution when results from different spectrophotometric equations are compared directly. Overall, the updated graph confirms that species identity, rather than analytical method, is the dominant source of variation in Chl a content in this dataset.

Chlorophyll b values

Chlorophyll b (Chl b) results exhibited a pattern consistent with that observed for Chl a; however, the ranking among methods differed slightly. In contrast to the previous interpretation, the Porra (2002) method generally yielded the highest Chl b values, followed by the Lichtenthaler & Wellburn (1983) method, while the Arnon (1949) method produced comparatively lower estimates across most species. Despite these numerical differences, one-way ANOVA indicated that the variation among methods was not statistically significant ($F=0.42$; $p=0.661$) (Figure 2). This suggests that the observed discrepancies in Chl b measurements are minor and likely attributable to methodological sensitivity rather than a consistent analytical bias.

From an interspecific perspective, *S. crispum* clearly exhibited the highest Chl b content across all methods, indicating a pronounced pigment accumulation capacity. This was followed by *R. tinctorum* and *P. tricuspidata*, which showed relatively elevated Chl b levels. In contrast, *C. radicans, L. japonica, P. quinquefolia,* and *W. sinensis* were characterized by comparatively lower Chl b concentrations (Figure 2). This distribution pattern highlights that Chl b variation is primarily species-dependent and may reflect differences in light adaptation strategies and photosynthetic apparatus organization among the studied taxa.

Given that chlorophyll b is associated with light-harvesting complexes and plays a crucial role in expanding the spectrum of absorbed light, higher Chl b levels particularly in species such as *S. crispum* may indicate an enhanced capacity for efficient light utilization, potentially linked to partial shade tolerance or adaptive plasticity in variable light environments. Moreover, although slight differences were observed among methods, Chl b concentrations remained consistently lower than Chl a across all species, which aligns with the well-established chlorophyll composition of higher plant leaves reported in the literature.

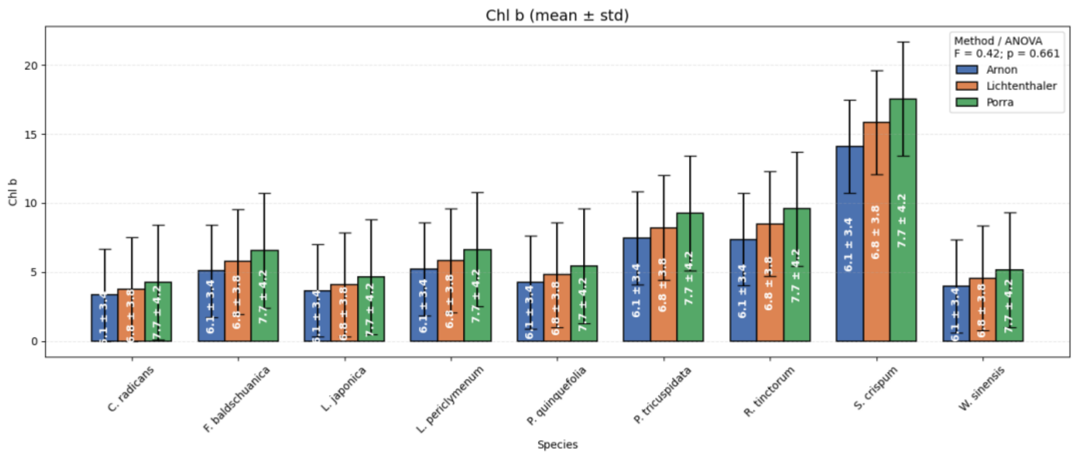

Figure 2. Chlorophyll b values of the studied species.
Şekil 2. *Türlere ait klorofil b değerleri.*

Overall, the updated results reinforce that species identity is the dominant factor influencing Chl b variation, while methodological differences among spectrophotometric approaches have a limited and statistically insignificant effect.

Total chlorophyll (Chl total)

When total chlorophyll (Chl total=Chl a + Chl b) values were evaluated across the three spectrophotometric methods, a pattern similar to that observed for individual pigments was identified. The Arnon (1949) method generally yielded the highest total chlorophyll values, followed by the Porra (2002) and Lichtenthaler & Wellburn (1983) methods, although the differences among methods were relatively small. One-way ANOVA results indicated that these differences were not statistically significant (F=0.11; p=0.896) (Figure 3). This finding demonstrates that the variation among methods is minimal and does not represent a consistent systematic bias, suggesting that all three methods provide comparable estimates of total chlorophyll content.

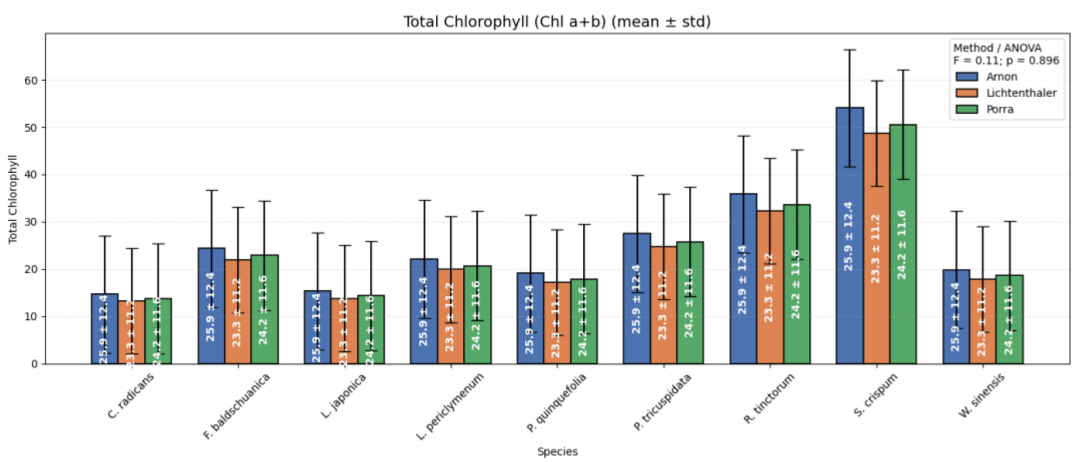

Figure 3. Total chlorophyll values of the studied species.
Şekil 3. *Türlere ait toplam klorofil değerleri.*

Among the species, *S. crispum* exhibited the highest total chlorophyll content by a substantial margin, confirming its strong photosynthetic pigment capacity. This was followed by *R. tinctorum* and *P. tricuspidata*, which also showed relatively high total chlorophyll levels. In contrast, *C. radicans* and *L. japonica* consistently displayed lower pigment concentrations, while the remaining species (*F. baldschuanica*, *L. periclymenum, P. quinquefolia,* and *W. sinensis*) occupied an intermediate position (Figure 3). These results clearly indicate that total chlorophyll content is primarily driven by species-specific physiological characteristics rather than methodological differences.

Although slight numerical differences were observed among the spectrophotometric methods, the overall ranking of species remained highly consistent. This consistency suggests that comparative interpretations of chlorophyll content across species are robust regardless of the method used. However, as previously noted in the literature, differences in extinction coefficients, solvent properties, and wavelength-specific calculations may still influence absolute pigment values. Therefore, it remains important to clearly specify the analytical method when comparing chlorophyll data across different studies.

Overall, the updated results reinforce that species identity is the dominant factor controlling total chlorophyll variation, while methodological differences among spectrophotometric approaches have a negligible and statistically insignificant effect.

Chlorophyll a/b ratios

The chlorophyll a/b ratio (Chl a/b) is a key physiological indicator reflecting the organization of the photosynthetic apparatus and the light adaptation strategy of plant leaves. In the present study, Chl a/b ratios generally ranged between approximately 2.0 and 3.5, which is consistent with the typical range reported for higher plants.

Among the spectrophotometric methods, the Lichtenthaler & Wellburn (1983) method consistently produced higher Chl a/b ratios, whereas the Porra (2002) method yielded comparatively lower values, and the Arnon (1949) method showed intermediate results. Unlike the findings for individual pigment concentrations (Chl a, Chl b, and total chlorophyll), one-way ANOVA revealed that the differences among methods were statistically significant ($F=19.47$; $p<0.001$). This result clearly indicates that the Chl a/b ratio is more sensitive to methodological differences than absolute pigment measurements.

This increased sensitivity can be explained by the fact that the ratio is derived from two independently estimated variables (Chl a and Chl b), meaning that even small deviations in either parameter can lead to amplified differences in the resulting ratio. Therefore, methodological variation in absorbance coefficients, solvent properties, extraction efficiency, or wavelength selection may disproportionately affect ratio-based calculations.

When all chlorophyll parameters (Chl a, Chl b, total chlorophyll, and Chl a/b ratio) are evaluated together, a consistent pattern emerges: species rankings remain largely stable across methods, while absolute values and ratio magnitudes exhibit systematic differences. Specifically, the Arnon method tends to produce higher absolute chlorophyll concentrations, the Lichtenthaler & Wellburn method yields higher Chl a/b ratios, and the Porra method generally provides lower ratio values.

Across all species, Chl values were consistently higher than Chl b, resulting in Chl a/b ratios greater than 1, which reflects the well-established pigment composition of higher plant leaves. From a physiological perspective, variations in the Chl a/b ratio may indicate differences in light acclimation strategies, with lower ratios typically associated with shade adaptation and higher ratios linked to sun-adapted conditions.

Overall, these findings emphasize the critical importance of method selection in ratio-based analyses. While absolute pigment concentrations appear robust across different spectrophotometric approaches, ratio-derived parameters such as Chl a/b are more susceptible to methodological variation. Therefore, strict methodological consistency is essential in comparative ecophysiological studies, and caution should be exercised when interpreting or comparing Chl a/b ratios obtained using different analytical methods.

Principal Component Analysis (PCA) (Lichtenthaler & Wellburn (1983) Method)

In the literature, the Lichtenthaler & Wellburn (1983) method is widely recognized as one of the most reliable and standardized approaches for the spectrophotometric determination of leaf pigments. Its widespread use is attributed to its reproducibility, well-established extinction coefficients, and extensive validation across diverse plant species (Lichtenthaler & Wellburn, 1983; Porra et al., 1989; Wellburn, 1994). Considering the absence of statistically significant differences among methods for Chl a, Chl b, and total chlorophyll in the present study, and the methodological robustness of the Lichtenthaler & Wellburn approach, interspecific comparisons were conducted based on the values obtained using this method.

Principal Component Analysis (PCA) results demonstrated that the first two principal components explained nearly all of the total variance among species (PC1: 98.6%; PC2: 1.4%; total: 100%) (Figure 4). This indicates that the variation in chlorophyll-related traits is overwhelmingly dominated by a single major gradient represented by PC1.

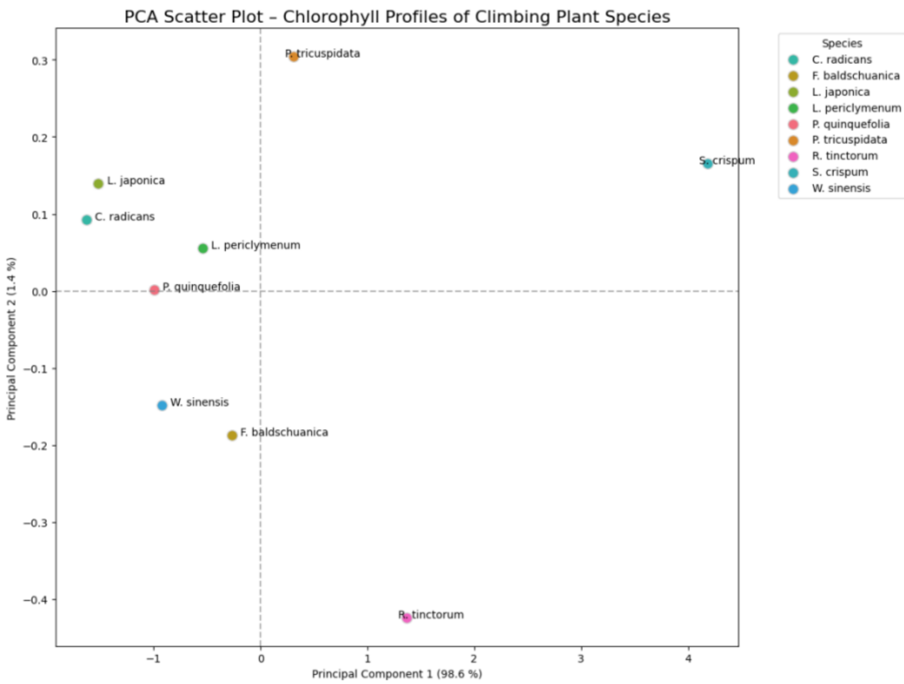

Figure 4. Principal component analysis (PCA) of studied species.

Şekil 4. *Türlerin Temel Bileşen Analizi (PCA) sonucu.*

The horizontal axis (PC1) represents the primary gradient of variation in chlorophyll content among species. Along this axis**,** *S. crispum* is clearly separated from all other species and positioned far on the positive side**,** indicating a distinctly higher chlorophyll profile and confirming its strong divergence in pigment composition. *R. tinctorum* also appears on the positive side of PC1 but is separated from S. crispum, suggesting relatively high but not extreme chlorophyll values. In contrast, the remaining species are clustered on the negative side of PC1, reflecting comparatively lower chlorophyll contents.

The vertical axis (PC2), which explains only a very small proportion of the variance (1.4%), represents minor secondary variation among species. Although its contribution is limited, it allows slight differentiation among species with similar chlorophyll levels. For example, *P. tricuspidata* is positioned in the upper part of the plot, while *F. baldschuanica* and *W. sinensis* are located in the lower region, indicating subtle differences in pigment composition that are not captured by PC1 alone. Similarly, *C. radicans, L. japonica, L. periclymenum***,** and *P. quinquefolia* are grouped relatively close to each other on the left side of the plot, suggesting broadly similar chlorophyll profiles.

Overall, the PCA clearly demonstrates that species are primarily separated along a single dominant axis (PC1), which reflects total chlorophyll variation, while secondary variation (PC2) plays only a minor role in species differentiation. The strong isolation of *S. crispum* highlights its unique physiological profile, whereas the clustering of the remaining species indicates relatively comparable pigment characteristics. These findings confirm that PCA is a powerful tool for visualizing interspecific differences in chlorophyll composition and reveal that species identity, rather than methodological differences, is the main driver of variation in chlorophyll profiles.

Cluster analysis (Dendrogram)

The hierarchical clustering dendrogram illustrates the similarity relationships among species based on their chlorophyll profiles. The analysis revealed a clear separation pattern, with species grouped according to their overall pigment composition (Figure 5).

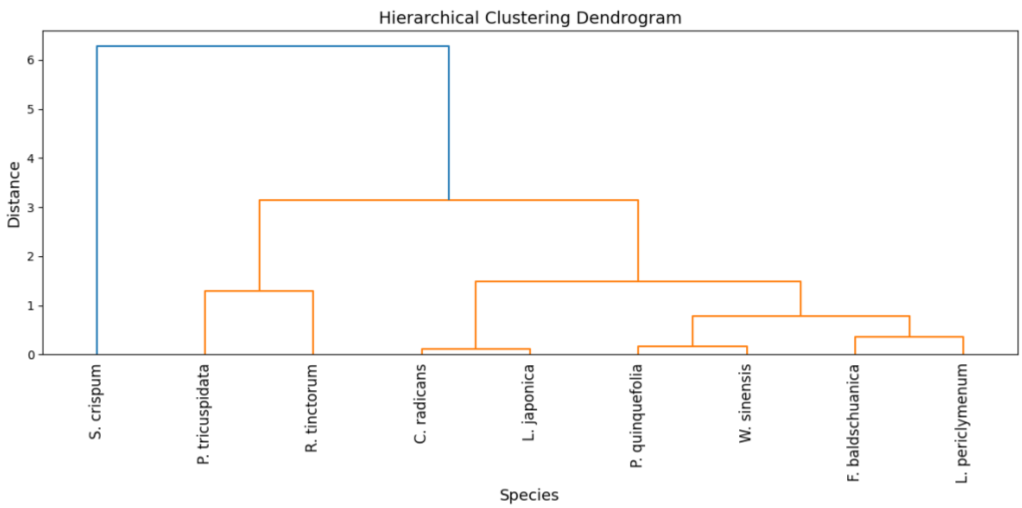

Figure 5. Dendrogram of studied species based on cluster analysis.
Şekil 5. *Kümeleme analizine dayalı tür dendrogramı.*

The most striking result is that *S. crispum* forms a distinct and isolated branch, separating from all other species at a relatively high distance level. This indicates that *S. crispum* possesses a markedly different chlorophyll profile compared with the remaining species, which is consistent with its significantly higher pigment content observed in previous analyses.

The remaining species form a second major cluster, within which several sub-groups can be identified. Among these, *P. tricuspidata* and *R. tinctorum* cluster closely together, indicating a high degree of similarity in their chlorophyll characteristics. This pair is then linked to a broader subgroup that includes *C. radicans* and *L. japonica*, which also exhibit relatively similar pigment profiles.

Another sub-cluster is formed by *F. baldschuanica* and *L. periclymenum*, which are closely associated and subsequently linked with *W. sinensis* and *P. quinquefolia*. These species generally represent intermediate to lower chlorophyll levels and show relatively small distances between each other, indicating comparable physiological characteristics.

Overall, the dendrogram demonstrates that most species share similar chlorophyll profiles and form a compact cluster, while *S. crispum* is clearly differentiated as an outlier species. The clustering pattern is largely consistent with the PCA results, confirming that species with similar pigment compositions are grouped together, whereas species with distinct chlorophyll characteristics are separated at higher linkage distances.

These findings indicate that chlorophyll-based clustering is an effective approach for distinguishing ecophysiological differences among climbing plant species, and that species identity plays a dominant role in determining pigment composition patterns.

The heat map hierarchical clustering analysis

The heat map hierarchical clustering analysis integrates chlorophyll parameters derived from the Lichtenthaler & Wellburn (1983) method with hierarchical clustering to provide a comprehensive visualization of pigment profiles among climbing plant species. Species are displayed along the vertical axis, while chlorophyll a (Chl a), chlorophyll b (Chl b), and total chlorophyll are presented on the horizontal axis. The color gradient represents standardized (z-score) values, where warmer colors indicate relatively higher values and cooler colors indicate lower values.

The heat map clearly reveals distinct interspecific variation in chlorophyll content. *S. crispum* is strongly distinguished from all other species by consistently high values across all chlorophyll parameters, forming a separate cluster. This pattern confirms its unique pigment profile and aligns with the results obtained from PCA and dendrogram analyses.

The remaining species form a relatively compact cluster characterized by moderate to low chlorophyll levels. Within this group, *R. tinctorum* and *P. tricuspidata* exhibit comparatively higher pigment values, whereas *C. radicans*, *L. japonica*, and *P. quinquefolia* show lower chlorophyll concentrations. Other species such as *F. baldschuanica*, *L. periclymenum*, and *W. sinensis* occupy intermediate positions, reflecting moderate pigment content.

The dendrogram structure associated with the heat map further demonstrates that species with similar chlorophyll profiles are grouped closely together, while those with distinct pigment characteristics are separated at higher linkage distances. In particular, the clear isolation of *S. crispum* highlights its strong divergence in pigment composition, whereas the clustering of the remaining species indicates relatively similar physiological characteristics.

Overall, this integrated visualization approach effectively captures both numerical and structural patterns in chlorophyll data, confirming that species identity is the primary determinant of variation in pigment composition. Moreover, the consistency between heat map, PCA, and clustering results strengthens the reliability of the observed patterns. Such analyses provide valuable insights into ecophysiological differences among species and can support informed species selection in landscape and ecological applications.

CONCLUSION and EVALUATION

The chlorophyll a/b ratios obtained in this study provide important ecophysiological insights into the light adaptation strategies of the examined climbing and vine plant species. In general, Chl a/b ratios above 2 indicate the predominance of heliophytic (sun-adapted) characteristics in most species. Relatively high chlorophyll a/b ratios observed in species such as *R. tinctorum* and *S. crispum* suggest that these plants may exhibit efficient photosynthetic performance under high light conditions. In contrast, the lower ratios observed in species such as *C. radicans* and *L. japonica* indicate that these plants may possess greater shade tolerance and exhibit mesophytic leaf characteristics.

Evaluation of total chlorophyll content revealed that *S. crispum* clearly stands out with the highest pigment concentrations among all species. This indicates that this species has a higher photosynthetic pigment capacity and a distinct physiological profile. *R. tinctorum* and *P. tricuspidata* also exhibit relatively high chlorophyll levels, whereas *C. radicans*, *L. japonica*, and *P. quinquefolia* display comparatively lower pigment concentrations. The remaining species (*F. baldschuanica*, *L. periclymenum*, and *W. sinensis*) occupy intermediate positions in terms of chlorophyll content.

These findings indicate that chlorophyll pigment amounts and Chl a/b ratios are closely related to plant light adaptation strategies and that these parameters can serve as useful physiological indicators in the ecophysiological characterization of species. The strong separation of *S. crispum*, as revealed by PCA and cluster analyses, further confirms that species-specific physiological traits are the primary drivers of variation in pigment composition.

Considering the semiarid climate conditions of Van, species selection in landscape design should take into account not only aesthetic characteristics but also physiological adaptability and environmental suitability. In this context, pigment-based physiological analyses can contribute to more informed species selection for sustainable landscape planning in semiarid regions. Among the studied species, *S. crispum* emerges as the most prominent candidate for vertical greening applications due to its high chlorophyll content and strong physiological performance, followed by *R. tinctorum* and *P. tricuspidata*, which also exhibit favorable pigment characteristics under high light conditions.

Landscape architecture assessment: chlorophyll ratios and vertical planting

Beyond the physiological performance of plants, the Chl a/b ratios and total pigment contents determined in the study provide a useful ecophysiological basis for species selection in the planting design of vertical surfaces and wall systems. Species with high photosynthetic capacity and relatively high Chl a/b ratios (*S. crispum* and *R. tinctorum*) may offer advantages in terms of tolerance to high light exposure, especially on surfaces receiving intense radiation, such as south-facing facades. These characteristics suggest that these species may be suitable candidates for vertical gardens and green facade systems.

Species with lower Chl a/b ratios (*C. radicans* and *L. japonica*) may perform more successfully under shaded or semi-shaded conditions, such as north-facing facades, inner courtyards, or narrow street canyons. This approach can contribute to both increasing visual diversity and improving ecological suitability in urban planting design. Additionally, species with relatively high pigment concentrations (*S. crispum, R. tinctorum*, and *P. tricuspidata*) may support higher photosynthetic activity and evapotranspiration capacity, which can contribute to urban microclimate regulation through shading and cooling effects.

In this context, chlorophyll-related physiological parameters may be considered among the useful indicators that can be integrated into landscape planning for urban climate-responsive design. This study evaluated the chlorophyll pigment contents of climbing and creeping plants commonly used in the semiarid city of Van in order to assess their physiological suitability for urban green infrastructure applications. Although differences in absolute chlorophyll values were observed among the three different spectrophotometric methods used in the measurements (Arnon, 1949; Lichtenthaler & Wellburn, 1983; Porra, 2002), similar overall patterns were obtained across the methods. However, a statistically significant difference was found between the methods in the Chl a/b ratio ($p<0.001$), highlighting the importance of methodological consistency, particularly in ratio-based ecophysiological interpretations.

The following conclusions were reached based on the research findings:

Use of chlorophyll parameters as physiological indicators: Chl a and Chl b contents together with the Chl a/b ratio can serve as useful physiological indicators for evaluating the adaptability of climbing plants used in semiarid environments such as Van.

Species selection and light adaptation: Heliophytic species (*S. crispum* and *R. tinctorum*) may be more suitable for high-light facades, whereas shade-tolerant species (*Lonicera spp*. and *C. radicans*) may perform better in shaded environments.

Implementation and design implications: This study highlights the importance of integrating plant physiological characteristics into species selection strategies for vertical greening systems in semiarid urban climates.

Overall, these results provide a scientific framework for supporting sustainable and functional green infrastructure planning in urban landscape design and emphasize the importance of ecophysiologically informed species selection.

The results of this study provide valuable insights for species selection in vertical greening systems in semiarid urban environments. Chlorophyll pigment profiles indicate that species such as *S. crispum* and *R. tinctorum* exhibit relatively high chlorophyll concentrations and favorable Chl a/b ratios, suggesting strong photosynthetic performance under high light conditions and making them suitable for highly exposed façades such as south- and west-facing building surfaces. In contrast, species such as *C. radicans* and *Lonicera spp*. (particularly *L. japonica* and *L. periclymenum*) show lower Chl a/b ratios and comparatively lower pigment contents, indicating greater tolerance to shaded environments such as north-facing façades, inner courtyards, or narrow urban street canyons. Integrating species with different light adaptation strategies into vertical planting systems can enhance both ecological functionality and visual diversity in urban landscapes. Moreover, species with relatively high pigment concentrations may contribute to urban microclimate regulation through shading and evapotranspiration, supporting climate-responsive green infrastructure design.

Overall, these findings emphasize that chlorophyll-based physiological parameters can serve as useful criteria for ecophysiologically informed species selection in vertical greening applications in semiarid cities such as Van.

Association with urban ecosystem services

Chlorophyll content is not only an indicator of plant physiological status but is also closely associated with important urban ecosystem services such as carbon sequestration, air quality improvement, and urban microclimate regulation. Species with relatively high photosynthetic pigment levels (*S. crispum, R. tinctorum,* and *P. tricuspidata)* may contribute more effectively to atmospheric CO_2 uptake and carbon storage potential (Nowak et al., 2006; Escobedo et al., 2011; Bowler et al., 2010; Perini & Rosasco, 2013). These species may also support urban thermal comfort through shading and evapotranspiration processes. In contrast, species with lower pigment content and relatively low Chl a/b ratios (*L. japonica*, *L. periclymenum,* and *C. radicans*) may provide ecological and aesthetic benefits in shaded urban environments. Therefore, chlorophyll-related physiological traits can serve as useful indicators for evaluating the potential contribution of climbing plants to urban ecosystem services.

The chlorophyll a/b ratios obtained in this study provide important ecophysiological insights into the light adaptation strategies of climbing plant species. Generally, Chl a/b ratios above 2 indicate the predominance of sun-adapted (heliophytic) leaf characteristics, while lower ratios may reflect greater shade tolerance. The relatively high Chl a/b ratios observed in *R. tinctorum* and *S. crispum* suggest that these species may maintain efficient photosynthetic performance under high light intensity. Conversely, lower ratios observed in *C. radicans* and *L. japonica* indicate a greater potential for adaptation to semi-shade or shaded conditions.

Evaluation of total chlorophyll content further revealed that *S. crispum* clearly stands out with the highest pigment concentrations, followed by *R. tinctorum* and *P. tricuspidata*, suggesting stronger photosynthetic capacity under high irradiance conditions. In contrast, *Lonicera species* (*L. japonica* and *L. periclymenum*) appear to be more compatible with semi-shaded environments due to their comparatively lower chlorophyll contents.

Landscape architecture interpretations regarding chlorophyll ratios and vertical/wall planting

Beyond their physiological significance, chlorophyll pigment contents and Chl a/b ratios provide useful ecological indicators for species selection in vertical planting systems and green façade design. Species with relatively high Chl a/b ratios and pigment contents (*R. tinctorum* and *S. crispum*) are likely to perform more effectively under intense light conditions and may therefore be suitable for highly exposed surfaces such as south-facing façades. These species may also require lower maintenance due to their ability to tolerate high irradiance and periodic water stress typical of semiarid urban environments. Conversely, species with lower Chl a/b ratios (*C. radicans* and *L. japonica*) may be more suitable for shaded conditions such as north-facing walls, inner courtyards, or narrow street canyons.

Furthermore, species with relatively high pigment concentrations (*S. crispum, R. tinctorum,* and *P. tricuspidata*) may contribute to urban microclimate regulation through shading and evapotranspiration processes, which can help mitigate urban heat island effects. In this context, chlorophyll-related physiological parameters may provide a scientific basis for integrating ecological functionality into landscape design decisions, particularly in vertical greening systems.

This study evaluated the photosynthetic pigment contents of climbing plant species commonly used in the semiarid city of Van in order to assess their physiological suitability for urban green infrastructure systems. Although differences in absolute chlorophyll values were observed among the three spectrophotometric methods used (Arnon, 1949; Lichtenthaler & Wellburn, 1983; Porra, 2002), the overall trends among species were consistent. However, a statistically significant difference was observed among methods in the Chl a/b ratio (p<0.001), indicating that methodological consistency is particularly important in ratio-based ecophysiological interpretations.

In conclusion, the results of this study indicate that chlorophyll pigment contents (Chl a and Chl b) and the Chl a/b ratio can serve as reliable physiological indicators for evaluating the adaptation capacity of climbing plants in semiarid urban environments such as Van. Species such as *S. crispum* and *R. tinctorum* exhibited relatively high chlorophyll content and Chl a/b ratios, suggesting a strong potential for photosynthetic performance under high light conditions and making them suitable candidates for sunny façade applications. *P. tricuspidata* also demonstrated relatively high pigment levels, indicating favorable physiological performance under similar conditions. In contrast, *L. japonica, L. periclymenum*, and *C. radicans* exhibited lower pigment concentrations and Chl a/b ratios, indicating better adaptation to semi-shaded or shaded environments.

These findings suggest that species selection for vertical greening systems and green façade applications should consider not only aesthetic characteristics but also physiological traits such as pigment composition and photosynthetic potential. Integrating such ecophysiological parameters into species selection strategies may support the development of more sustainable and climate-responsive urban green infrastructure systems. Moreover, chlorophyll-based physiological indicators may help landscape architects and urban ecologists design planting strategies that enhance ecosystem services such as carbon sequestration, urban cooling, and microclimate regulation (Speak et al., 2012; Perini & Ottelé, 2021).

Data Availability

Data will be made available upon reasonable request.

Author Contributions

Conception and design of the study: ŞA; sample collection: ŞA; analysis and interpretation of data: YP; statistical analysis: YP; visualization: ŞA; writing manuscript: YP.

Conflict of Interest

There is no conflict of interest between the authors in this study.

Ethical Statement

We declare that there is no need for an ethics committee for this research.

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