

Article

Relationship Between Courtyard Enclosure Forms and Autumn Dynamics of Façade Greening: A Field Study Based on Time-Series Monitoring of Microclimatic Fluctuations

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Abstract

Courtyard enclosure form and façade orientation are associated with near-wall microclimatic fluctuation and autumn façade-greening dynamics. This exploratory study monitored Boston ivy at six sample points in two-sided, three-sided, and four-sided enclosures with south-, west-, and north-facing façades. Near-wall temperature and relative humidity were recorded every 5 min, and fixed-ROI time-series imagery quantified leaf color change and defoliation. Mean thermal–humidity conditions varied modestly; daily temperature range varied from 8.79 ± 2.35 to 17.90 ± 7.21 °C and daily relative humidity range from $18.46 \pm 4.59\%$ to $29.81 \pm 7.38\%$. DI50 occurred from 20 October to 1 November and DI80 from 6 to 25 November. Spearman analysis of 60 matched daily observations showed stronger associations of mean thermal–humidity indicators than fluctuation indicators with phenological indicators. RMedian correlated positively with LCR ($\rho = 0.70$), while DI correlated negatively with RMedian and Color Index ($\rho = -0.50$ and -0.53). Because enclosure form and façade orientation were partly coupled, their effects could not be separated. Overall, sample points differed more clearly in thermal–humidity fluctuation than in mean conditions, while phenological differences reflected enclosure form, façade orientation, near-wall thermal–humidity conditions, and exposure conditions.

Keywords: urban microclimate; courtyard enclosure form; façade greening; Boston ivy; autumn phenology; image-based monitoring

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1. Introduction

Urbanization intensifies building density, hardens underlying surfaces, and reorganizes spatial enclosure, thereby altering radiation regimes, ventilation pathways, and heat–moisture exchange around buildings. These processes generate highly heterogeneous local microclimates [1,2]. Because plant phenology is sensitive to temperature, moisture, radiation, and humidity, it functions not only as a biological indicator of urban environmental change but also as a means of detecting how architectural spatial differences shape seasonal plant processes [3]. For plants attached to building façades, the growing environment is not equivalent to that of open green space or to the background climate recorded by regional weather stations. Instead, façade vegetation remains in close contact

with wall surfaces and is continuously conditioned by building interfaces, orientation, shading, and near-wall heat–moisture exchange. Previous studies have shown that urban environments can substantially alter flowering, leaf-out, leaf color change, and defoliation, and that such effects occur not only along urban–rural gradients but also within cities, across thermal and spatial micro-environments [4–6]. Although autumn leaf color change and defoliation have received less attention than spring phenology, recent work demonstrates that autumn phenology is also governed by local thermal conditions and cannot be adequately explained by regional meteorological data alone, because plants experience microclimates closer to the ground surface, wall surface, and canopy boundary [5,7,8]. From a broader bioclimatic-design perspective, this issue concerns how architectural spatial configuration conditions the environmental context and seasonal performance of façade greening. Courtyards can therefore be understood as intermediate-scale environmental units linking urban morphology, building-envelope design, and plant seasonal responses.

Three strands of literature frame the present study. First, research on urban plant phenology shows that temperature and humidity backgrounds influence the timing and duration of seasonal transitions, and that local microclimates can produce distinct phenological rhythms within the same city [2,3,5]. Valdés et al. further demonstrate that microclimate affects plant growth and reproductive performance through both direct and indirect pathways [9], while Díaz et al. note that the responses of different plant functional groups to urbanization do not follow a single directional pattern [6]. Autumn phenology studies are especially relevant here: local microclimate not only affects when leaves fall, but also shapes the onset and duration of leaf color change [7]. Nevertheless, much of this literature relies on urban plots, regional monitoring stations, or remote-sensing scales. It has paid insufficient attention to the near-wall attachment interface of building façades, where regional meteorological variables often fail to represent the micro-environment actually experienced by façade vegetation [5,6].

Second, façade greening research has established that building façades are not passive backgrounds for plant attachment. Rather, they co-produce near-wall microclimate systems with vegetation. Susorova et al. show that climbing plants can reduce exterior wall surface temperature, attenuate heat flux, and improve near-wall air conditions, with effects that vary by façade orientation [10]. Previous studies on façade greening and plant-related microclimate modeling have demonstrated that façade vegetation can modify building-envelope and near-wall thermal–moisture conditions through shading, transpiration cooling, insulation, and boundary-layer air exchange [11–15]. De Groeve et al. further argue that the near-surface microclimatic effects of façade greening are generally clear, but their intensity varies with plant type, attachment mode, material context, and exposure condition [13]. However, existing vertical greening studies have largely foregrounded summer cooling, building energy performance, and thermal comfort [13–15]. Far less attention has been given to autumnal leaf color change, declining leaf coverage, and the landscape transformation of deciduous façade vegetation [5–7]. For Boston ivy and similar deciduous vertical greening species, the more precise question is therefore whether different architectural micro-environments, under the same seasonal climatic background, alter the onset of autumn coloration, the duration of color transition, and the speed of defoliation.

Third, within bioclimatic design, courtyards are not merely spatial voids between buildings but passive environmental modifiers whose performance depends on the interaction of spatial configuration, climatic conditions, and surface characteristics [16–18]. Courtyard geometry, degree of enclosure, façade orientation, and opening arrangement regulate solar access, shading duration, radiative exchange, and airflow, thereby affecting heat accumulation and dissipation within enclosed outdoor spaces [16,17,19,20]. Surface

materials, vegetation, and moisture-related landscape elements further modify heat storage, evapotranspiration, and local thermal–humidity conditions [17,18]. Courtyards may therefore provide different seasonal benefits, including improved solar access and wind protection during cold periods and increased shading and ventilation during warm periods. However, these benefits are not produced by enclosure form alone. They result from the combined effects of enclosure, orientation, openings, building height, surface treatment, vegetation, and the prevailing climatic background [16–18]. Courtyard performance should therefore be understood as climate- and season-dependent rather than as an inherent advantage of a particular enclosure form. Nevertheless, existing studies have primarily evaluated courtyard performance in relation to thermal comfort, open-space optimization, and building-energy demand, and have rarely connected these bioclimatic functions with the seasonal phenology of façade greening [13,18].

Methodologically, fixed cameras, time-series imagery based on fixed regions of interest (ROI), and RGB/grayscale channel metrics provide a feasible route for monitoring seasonal plant dynamics [21–24]. Richardson et al. demonstrated early on that digital webcam imagery can track seasonal change in deciduous broadleaf forests [21]. Sonnentag et al. systematically clarified the advantages of digital repeat photography for forest phenology [22], while Alberton and Filippa advanced standardization in image-based phenological monitoring and computational workflows [23,25]. Brown, Zhang, Sunoj, and Cao extended this methodological framework across forests, urban vegetation, crop systems, and image recognition applications [26–29]. Integrating time-series imagery with building courtyard microclimate monitoring therefore makes it possible to translate the theoretical issues outlined above into observable and comparable process indicators.

Overall, previous research has established three relevant relationships separately. Local urban environmental conditions are associated with the timing and progression of plant phenology [2,5]. Façade greening interacts with building surfaces and near-wall environments through shading, transpiration, insulation, and boundary-layer exchange [13,15]. Courtyard geometry and orientation, in turn, reorganize radiation access, shading patterns, and airflow conditions [16,18]. However, these relationships remain insufficiently connected at the courtyard–façade scale, particularly during the autumn transition of deciduous façade vegetation. Existing studies have rarely distinguished mean thermal–humidity conditions from diurnal variability or treated leaf coloration and defoliation as related but potentially asynchronous components of seasonal performance.

This gap is relevant to the broader field of bioclimatic design because the performance of façade greening should not be assessed solely in terms of summer cooling and thermal regulation. For deciduous façade greening, seasonal performance also includes color expression, leaf-retention duration, and the timing and progression of defoliation. The present study therefore addresses the broader question of how bioclimatic courtyard design can account for the seasonal, rather than exclusively summer thermal, performance of deciduous façade greening. Examining these processes at the courtyard–façade scale extends bioclimatic assessment towards a more seasonal and spatially specific understanding of façade-greening performance.

Building on this gap, this study examines Boston ivy façades within a university courtyard, focusing on the associations among enclosure form, façade orientation, near-wall thermal–humidity conditions, and image-derived phenological indicators under a shared seasonal background. Specifically, the study addresses the following four questions:

- (1) How are the monitored courtyard enclosure–orientation settings associated with near-wall thermal–humidity conditions, and are the observed differences more evident in mean conditions or in diurnal fluctuations?

- (2) How do the timing, duration, and synchrony of autumn leaf color change and defoliation vary across the monitored enclosure–orientation settings?
- (3) To what extent are near-wall thermal–humidity indicators associated with image-derived indicators of leaf color change and defoliation?
- (4) Under a shared seasonal background, how do courtyard spatial configurations defined by enclosure form and façade orientation condition the temporal structure and progression of autumn leaf coloration and defoliation?

Based on the above research questions, this study establishes an integrated workflow that connects courtyard enclosure form, near-wall microclimate monitoring, fixed-ROI time-series imagery, and image-derived phenological indicators. As illustrated in Figure 1, the analysis proceeds from spatial classification and field monitoring to indicator construction, time-series comparison, key-stage extraction, and correlation analysis. This workflow provides the methodological bridge between the conceptual framework proposed in the Introduction and the detailed procedures described in Section 2.

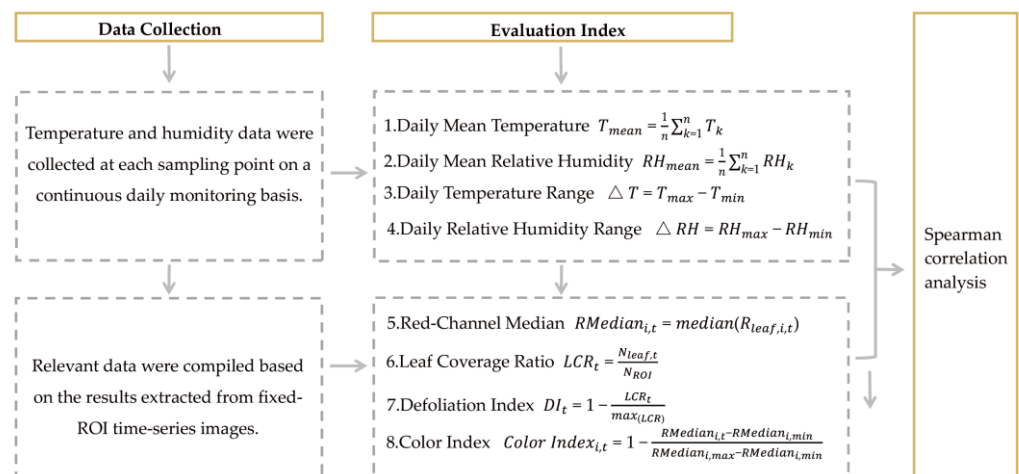


Figure 1. Workflow of microclimate and phenological indicator construction and statistical analysis.

2. Materials and Methods

2.1. Study Object and Spatial Typology

This study selected Boston ivy (*Parthenocissus tricuspidata*) façades in a university courtyard as the research object. The sample points were located within the same campus building cluster, shared the same regional seasonal background, and involved the same plant type. This setting provided a suitable basis for observing how architectural micro-spaces modulate the autumnal processes of façade greening. To avoid reducing architectural space to planar closure, this study defines enclosure form as a spatial condition constituted by the number of effective surrounding building interfaces, the primary opening orientation, the façade orientation, and their combined effects on radiation access and air exchange [1,16,17,30]. The study site, sample-point distribution, enclosure classification, and façade orientations are shown in Figure 2.

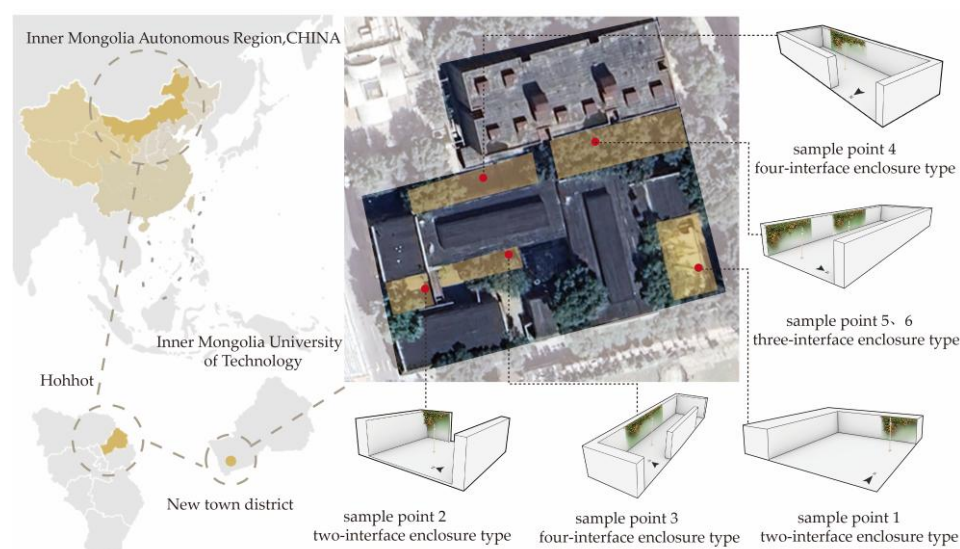


Figure 2. Study site, sample-point distribution, enclosure classification, and façade orientations.

Based on the number of effective surrounding building interfaces, the sample points were classified into three enclosure types: two-sided, three-sided, and four-sided enclosed spaces. The two-sided category included Sample Point 1, where Boston ivy was located on a south-facing façade, and Sample Point 2, where it was located on a west-facing façade. The three-sided category included Sample Points 5 and 6, both with Boston ivy on north-facing façades. The four-sided category included Sample Point 3, with Boston ivy on a south-facing façade, and Sample Point 4, with Boston ivy on a north-facing façade.

This classification captures differences in courtyard openness, spatial shading, ventilation pathways, and radiation reception. At the same time, enclosure form and orientation are partly coupled in some sample points. To avoid over-interpretation, the following results and discussion describe the effects of enclosure as moderating effects rather than as strict single-cause relationships.

2.2. Microclimate Monitoring and Variable Construction

Temperature and humidity data loggers were installed within the projected range of the Boston ivy at each sample point. They were mounted on brackets approximately 1.5 m above ground level and recorded temperature and relative humidity at 5 min intervals. The specifications of the monitoring instruments are listed in Table 1. This height was selected to approximate the near-wall environment experienced by the plants and the human perception layer, while reducing direct ground-surface interference. Raw observations were aggregated by date to generate daily scale microclimate indicators. The observation period extended from 15 October 2025 to 25 November 2025, covering the main autumn coloration and defoliation period of Boston ivy in the study area.

Table 1. Specifications of the monitoring instruments used for microclimate measurement and image acquisition.

Instrument Name	Measurement Range	Measurement Accuracy	Illustration
Temperature and Humidity Data Logger (Model: RC-4HC)	Temperature: −30 °C to 60 °C Relative Humidity (RH): 0% to 100%	Temperature: ±0.5 °C Humidity: ±3% RH	
Apple iPhone 16 Pro (rear camera; Apple Inc., Cupertino, CA, USA)	Focal length: 13 mm to 120 mm	Image resolution: 48 MP (megapixels)	

The microclimate indicators were designed to capture two dimensions: mean state and fluctuation. Mean-state indicators included daily mean temperature (T_{mean}) and daily mean relative humidity (RH_{mean}), which characterize the basic thermal–humidity background of each space. Fluctuation indicators included daily temperature range (ΔT) and daily relative humidity range (ΔRH), which respectively represent the intra-day amplitude of temperature and humidity variation and indicate environmental stability, buffering capacity, and sensitivity to external climatic disturbance. Specifically, ΔT was calculated as the difference between the daily maximum and minimum temperature, while ΔRH was calculated as the difference between the daily maximum and minimum relative humidity. Daily minimum temperature (T_{min}), daily maximum temperature (T_{max}), daily minimum relative humidity (RH_{min}), and daily maximum relative humidity (RH_{max}) were also retained as auxiliary indicators for the correlation analysis. These extrema were used to examine whether the upper and lower bounds of daily thermal–humidity conditions were associated with the image-derived phenological indicators; whereas, T_{mean} , RH_{mean} , ΔT , and ΔRH remained the primary indicators used for the descriptive and between-setting comparisons. In this study, air temperature and relative humidity were used to characterize the thermal–humidity dimension, rather than the full range of microclimatic processes, within the near-wall environment.

2.3. Time-Series Image Acquisition, Color Gradient Skewness Distribution Parameters, and Defoliation Index Calculation

As shown in Figure 3, this study used fixed-ROI time-series photography to continuously characterize leaf color change and defoliation. For all sample points, the camera position and viewing angle were kept as consistent as possible. Image acquisition was conducted between 14:00 and 16:00 on each observation day to improve temporal comparability and reduce the influence of diurnal illumination variation [22,23,27]. A fixed ROI was defined on the first image of each sample point, and subsequent images retained the same frame to ensure comparability across dates. Image processing involved three steps. First, ROI images were background-removed in Adobe Photoshop 2018 and exported as transparent PNG files. Second, the RGBA pixel matrix was read, and the alpha channel was used to identify leaf pixels while excluding wall surfaces, sky, and other background elements. Third, the mean, median, mode, skewness, and kurtosis of the R, G, B, and gray-scale channels were calculated for leaf pixels, forming the Color Gradient Skewness

Distribution (CGSD) parameter system used to describe the color-distribution characteristics of leaves [29].

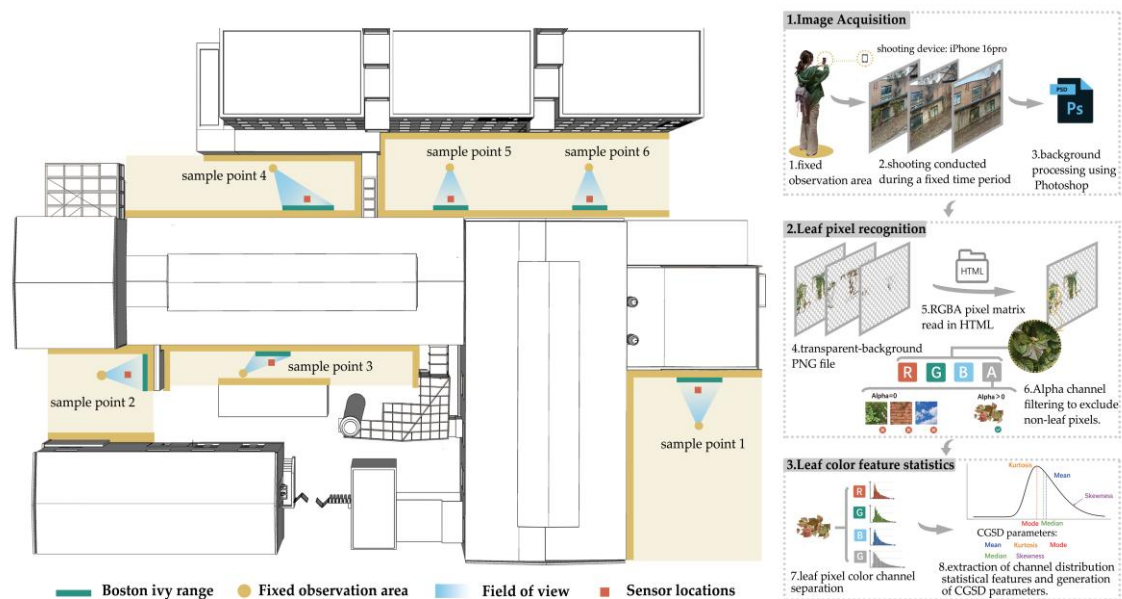


Figure 3. Fixed-ROI time-series photography workflow used to characterize leaf color change and defoliation.

The Leaf Coverage Ratio (LCR) draws on the concept of fractional vegetation cover (FVC/FCover), which expresses coverage as the proportion of vegetation pixels within a defined analytical area [31]. In this study, LCR was operationalized as the proportion of leaf pixels within a fixed ROI and was used to characterize changes in leaf cover on the façade. Leaf cover dynamics were quantified using the Leaf Coverage Ratio (LCR) and the Defoliation Index (DI). LCR was defined as:

$$LCR_t = \frac{N_{leaf,t}}{N_{ROI}} \quad (1)$$

where N_{ROI} pixels denotes the total number of pixels within the fixed ROI, and $N_{leaf,t}$ pixels denotes the number of pixels identified as leaves.

To enable comparison across dates and to remove the influence of differences in initial coverage among sample points, a normalized Defoliation Index was further constructed:

$$DI_t = 1 - \frac{LCR_t}{\max(LCR)} \quad (2)$$

where $\max(LCR)$ is the maximum LCR observed at the same sample point during the entire monitoring period. A DI value approaching 1 indicates severe leaf loss; whereas, a DI value close to 0 indicates that leaf cover remains near the maximum observed state for that sample point. To identify key phenological stages, $DI = 0.5$ and $DI = 0.8$ were used as working thresholds. DI_{50} and DI_{80} were defined as the dates on which the Defoliation Index first reached 0.5 and 0.8, respectively, representing mid-stage defoliation and near-complete defoliation. These thresholds are descriptive indicators for comparing sample points and should not be interpreted as universal physiological thresholds.

To reduce processing bias, all ROI extraction and background removal were conducted using the same workflow. The ROI boundary for each sample point was defined on the first valid image and kept unchanged throughout the monitoring period. Images with severe occlusion, rainfall blur, or extreme exposure were excluded before analysis. Because no physical color-calibration card was used during field photography, RMedian and Color Index were interpreted as relative within-point temporal indicators rather than

absolute colorimetric measurements. Accordingly, comparisons among the six sites focused on temporal trajectories, while their absolute numerical values were not considered directly comparable across sites or with those reported in other studies.

2.4. Construction of the Leaf Color Change Indicator

For leaf color change, the red-channel median (RMedian) was used as the primary indicator, and a standardized Color Index was further constructed [23,28,29]. The median was selected rather than the mean or mode because it is less sensitive to local highlights, shadow edges, and small numbers of anomalous pixels, making it more suitable for outdoor fixed-ROI time-series comparison. During autumn coloration, the red channel is sensitive to the transition from green to yellow and red tones; consequently, RMedian provides a relatively stable representation of leaf color change intensity.

To improve comparability across sample points, the original RMedian values at each point were standardized as follows:

$$\text{Color Index}_{i,t} = \frac{\text{RMedian}_{i,t} - \text{RMedian}_{i,\min}}{\text{RMedian}_{i,\max} - \text{RMedian}_{i,\min}} \quad (3)$$

where $\text{RMedian}_{i,t}$ denotes the red-channel median of sample point i on date, and $\text{RMedian}_{i,\min}$ and $\text{RMedian}_{i,\max}$ denote the minimum and maximum RMedian values observed at that sample point over the monitoring period. After standardization, the Color Index ranges from 0 to 1 and indicates the relative position of a given date within the color-change trajectory of that sample point.

2.5. Statistical Analysis

The raw monitoring data were processed and statistically analyzed on a daily basis. First, continuous temperature–humidity data from each sample point were aggregated by date to calculate Tmean, RHmean, ΔT , and ΔRH . Second, the fixed-ROI time-series image results were used to derive RMedian, LCR, DI, and Color Index, which characterize autumn leaf color change and defoliation in Boston ivy. Third, microclimate data and image-derived indicators were merged by sample point and date. The sample points were then grouped by spatial form into two-sided, three-sided, and four-sided enclosed spaces for time-series comparison, between-group comparison, and key-stage extraction. Relationships between daily thermal–humidity indicators—including the primary indicators Tmean, RHmean, ΔT , and ΔRH and the auxiliary extrema Tmin, Tmax, RHmin, and RHmax—and image-derived phenological indicators (RMedian, LCR, DI, and Color Index) were examined using Spearman’s rank correlation analysis. All correlations were based on 60 valid site–date observations matched by sample point and observation date. Because the dataset comprised repeated and temporally ordered observations from the six sample points, the 60 site–date observations were not assumed to be fully independent. The correlations were therefore interpreted as exploratory contemporaneous associations rather than causal effects. Temporal autocorrelation, site-level random effects, and possible lagged phenological responses were not explicitly modeled. Statistical significance was evaluated at $p < 0.05$ and $p < 0.01$. Timeline analysis, between-group comparison, and the correlation heatmap were used in combination to interpret the temporal structure of autumn phenological change.

3. Results

3.1. Microclimatic Differences Under Different Enclosure–Orientation Conditions

To examine how architectural micro-spaces were associated with near-wall microclimate, this section compares the six sample points from both time-series and between-group perspectives. Because enclosure form and façade orientation were not fully independent in the current dataset, the results are interpreted as differences among enclosure–

orientation conditions rather than as independent enclosure-form effects. Overall, daily mean temperature and daily mean relative humidity differed only modestly among enclosure types; whereas, daily temperature range and daily relative humidity range showed clearer differentiation.

Figure 4 shows the time-series variation in daily mean temperature, daily mean relative humidity, daily temperature range, and daily relative humidity range during the observation period. The mean thermal–humidity background followed broadly similar temporal trends across sample points, indicating that all points were shaped by the shared regional seasonal process. By contrast, differences in intra-day fluctuation were more pronounced, suggesting that building enclosure form is more likely to operate by modifying environmental stability and buffering capacity against external climatic disturbance. Based on the time-series comparison, Tmean, RHmean, ΔT , and ΔRH were further summarized by enclosure type.

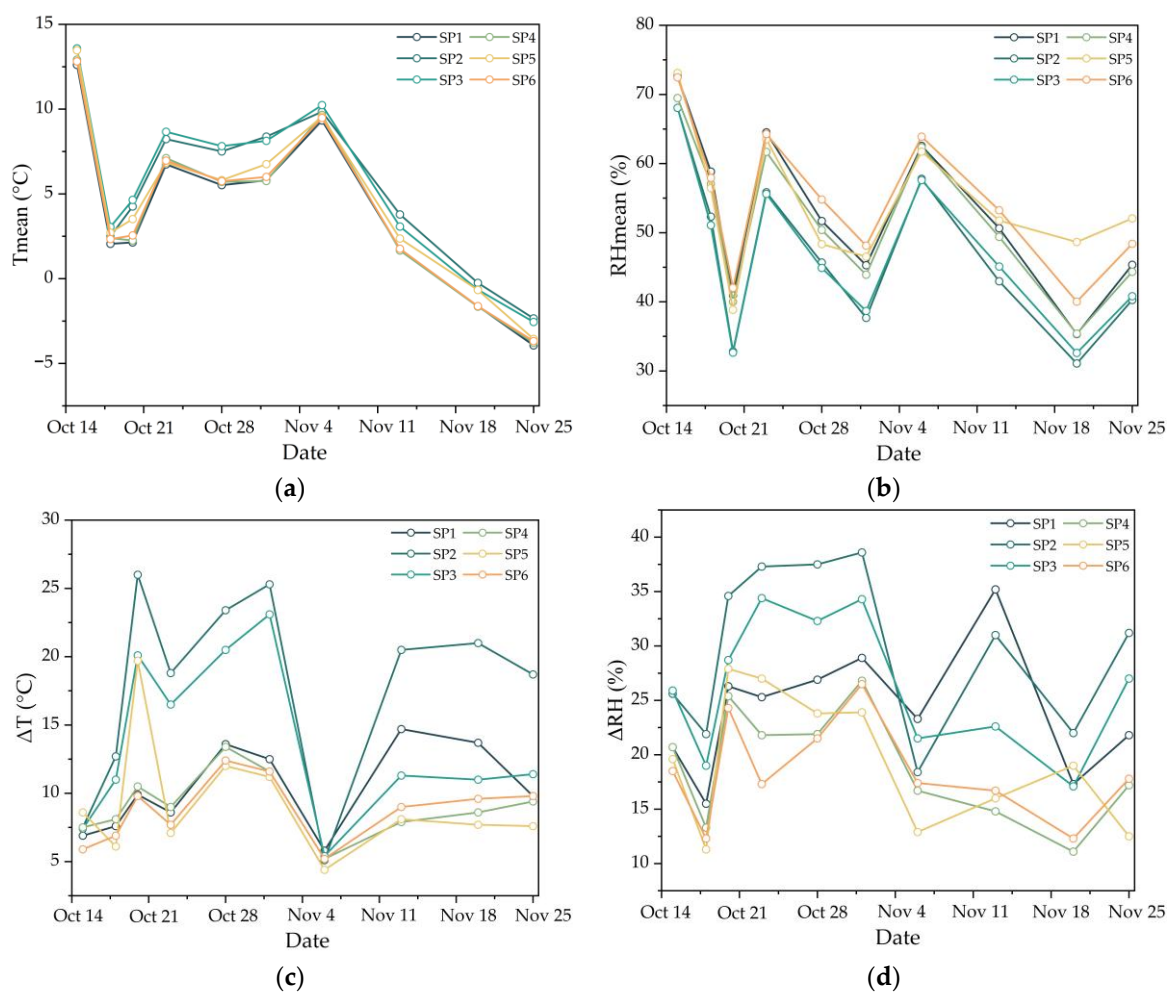


Figure 4. Time-series variation in microclimate indicators at the six sample points from 15 October to 25 November 2025: (a) daily mean temperature, (b) daily mean relative humidity, (c) daily temperature range, and (d) daily relative humidity range. SP1–SP6 denote Sample Points 1–6, respectively.

As shown in Table 2, daily mean temperature varied within a relatively narrow range among sample points, from 4.04 ± 4.97 °C at SP1 to 5.60 ± 5.00 °C at SP3. RHmean ranged from $46.45 \pm 11.87\%$ at SP2 to $54.52 \pm 10.34\%$ at SP6. In contrast, fluctuation indicators showed clearer differentiation: ΔT ranged from 8.79 ± 2.35 °C at SP6 to 17.90 ± 7.21 °C at SP2, and ΔRH ranged from $18.46 \pm 4.59\%$ at SP6 to $29.81 \pm 7.38\%$ at SP2. This suggests that

local architectural differences were more clearly reflected in intra-day thermal–humidity fluctuation than in daily mean conditions.

Table 2. Descriptive statistics of daily microclimate indicators at each sample point.

Sample Point	Enclosure Type	Façade Orientation	Tmean/°C	RHmean/%	ΔT /°C	ΔRH /%
SP1	Two-sided	South-facing	4.04 ± 4.97	52.78 ± 11.68	10.31 ± 3.15	24.12 ± 5.75
SP2	Two-sided	West-facing	5.54 ± 4.84	46.45 ± 11.87	17.90 ± 7.21	29.81 ± 7.38
SP3	Four-sided	South-facing	5.60 ± 5.00	46.71 ± 11.42	13.77 ± 5.94	26.28 ± 6.21
SP4	Four-sided	North-facing	4.20 ± 5.06	51.40 ± 10.96	9.12 ± 2.29	18.97 ± 5.19
SP5	Three-sided	North-facing	4.68 ± 4.93	54.10 ± 9.86	9.25 ± 4.29	19.39 ± 6.12
SP6	Three-sided	North-facing	4.24 ± 4.98	54.52 ± 10.34	8.79 ± 2.35	18.46 ± 4.59

Figure 5 further compares the distribution of microclimate indicators among two-sided, three-sided, and four-sided enclosed spaces. The results indicate that while average temperature and humidity conditions show limited variation across different enclosure types, the amplitude of their fluctuations differs more markedly. This suggests that the primary role of enclosure morphology is to modulate local microclimatic variability, rather than to determine its average state.

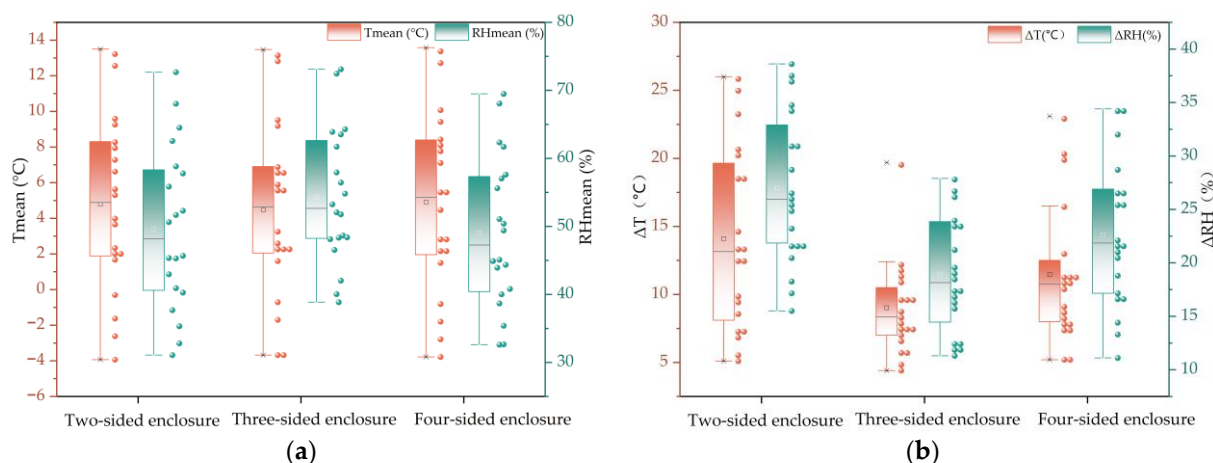


Figure 5. Inter-group comparison of microclimate indicators under different building enclosure types: (a) daily mean temperature and relative humidity; (b) daily temperature and humidity ranges. The boxes represent the interquartile range, the horizontal lines within the boxes indicate the medians, the square markers indicate the means, the whiskers indicate the spread of the data beyond the boxes, and the scattered points represent individual observations.

3.2. Phenological Stages and Rhythms Under Different Spatial Conditions

The monitoring period was segmented into three stages according to DI values: Stage I (DI < 0.5, high leaf cover), Stage II (0.5 ≤ DI < 0.8, mid-stage defoliation), and Stage III (DI ≥ 0.8, near-complete defoliation). Based on RPeak, DI50, and DI80, a timeline of key phenological dates was established for each sample point (Figure 6).

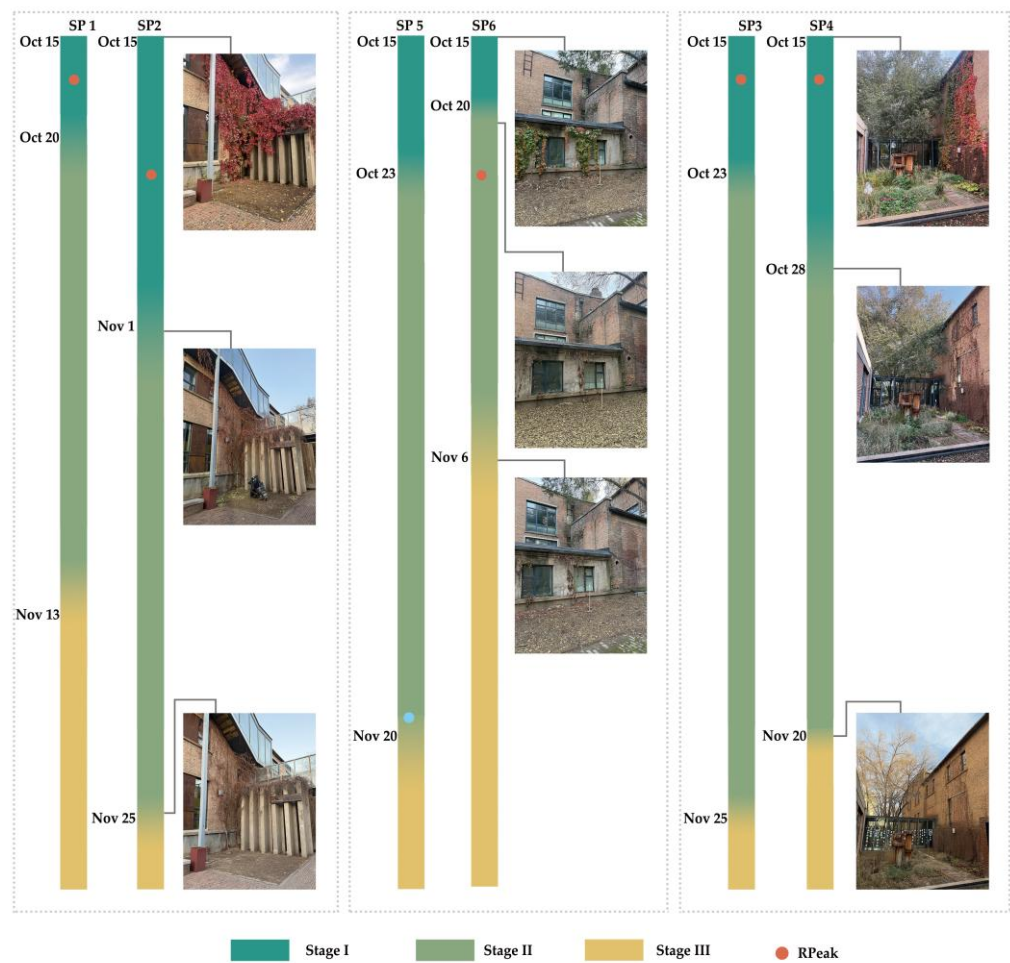


Figure 6. Timeline of key phenological dates for Boston ivy at the six sample points. RPeak denotes the date of maximum RMedian, while DI50 and DI80 denote the first dates when DI reached 0.5 and 0.8, respectively. Stages I–III represent the three defoliation stages.

As shown in Table 3, RPeak, DI50, and DI80 did not occur simultaneously across sample points. SP1 and SP6 reached DI50 earliest on 20 October 2025; whereas, SP2 reached DI50 latest on 1 November 2025. SP6 reached DI80 earliest on 6 November 2025, while SP2 and SP3 reached DI80 latest on 25 November 2025. Stage II duration ranged from 17 days at SP6 to 33 days at SP3, indicating different rates of transition from mid-stage to near-complete defoliation.

Table 3. Key phenological dates and stage durations derived from image-based indicators.

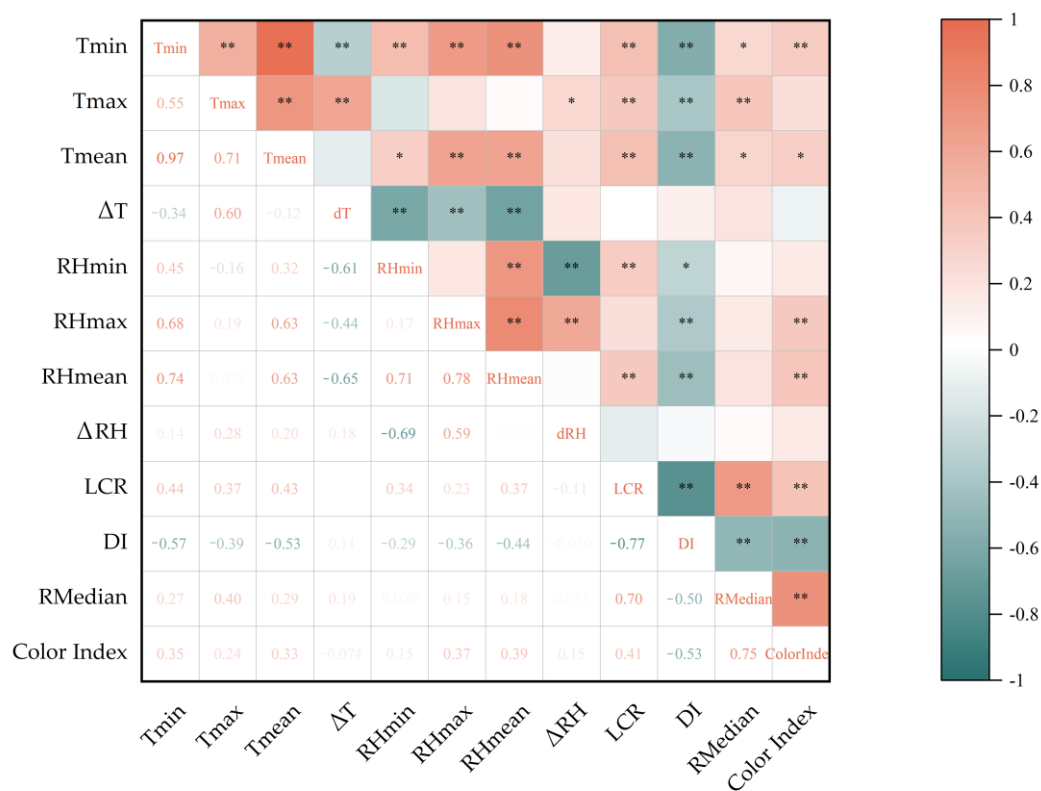
Sample Point	Enclosure Type	Façade Orientation	RPeak Date	DI50 Date	DI80 Date	Stage I Duration/Days	Stage II Duration/Days	Stage III On-set
SP1	Two-sided	South-facing	18 October 2025	20 October 2025	13 November 2025	5	24	13 November 2025
SP2	Two-sided	West-facing	23 October 2025	1 November 2025	25 November 2025	17	24	25 November 2025
SP3	Four-sided	South-facing	18 October 2025	23 October 2025	25 November 2025	8	33	25 November 2025
SP4	Four-sided	North-facing	18 October 2025	28 October 2025	20 November 2025	13	23	20 November 2025

SP5	Three-sided	North-facing	20 November 2025	23 October 2025	20 November 2025	8	28	20 November 2025
SP6	Three-sided	North-facing	23 October 2025	20 October 2025	6 November 2025	5	17	6 November 2025

These differences indicate that leaf color change and leaf-cover decline were asynchronous. DI50 and DI80 should be interpreted as descriptive comparison thresholds rather than fixed physiological markers. Overall, the results suggest that architectural micro-spaces were associated with distinguishable phenological rhythms under a shared seasonal background.

3.3. Associations Among Microclimate and Image-Derived Phenological Indicators

After identifying the key phenological stages, this study examined contemporaneous associations between the daily thermal-humidity indicators and image-derived phenological indicators. The correlation analysis included the four primary indicators (Tmean, RHmean, ΔT , and ΔRH) and four auxiliary extrema (Tmin, Tmax, RHmin, and RHmax). Spearman's rank correlations were calculated using 60 valid site-date observations matched by sample point and observation date, and the resulting correlation matrix is presented in Figure 7.



* $P < 0.05$ ** $P < 0.01$

Figure 7. Spearman correlation heatmap between microclimate indicators and image-derived phenological indicators.

As shown in Table 4, LCR was strongly and negatively correlated with DI ($q = -0.77$, $p < 0.001$), confirming the internal consistency of the defoliation indicator. RMedian was strongly and positively correlated with Color Index ($q = 0.75$, $p < 0.001$). DI was negatively correlated with both RMedian ($q = -0.50$, $p < 0.001$) and Color Index ($q = -0.53$, $p < 0.001$), suggesting that defoliation and color change were related but not identical processes.

Because the observations were temporally ordered, these correlations are interpreted as descriptive associations rather than causal evidence.

Table 4. Spearman correlations among image-derived phenological indicators.

Variable Pair	Spearman's ρ	p -Value
LCR—DI	−0.77	<0.001
LCR—RMedian	0.70	<0.001
LCR—Color Index	0.41	<0.001
DI—RMedian	−0.50	<0.001
DI—Color Index	−0.53	<0.001
RMedian—Color Index	0.75	<0.001

Note: Spearman's ρ was calculated using 60 valid site–date observations from the six sample points. Because these observations were repeated and temporally ordered, the correlations are interpreted as exploratory associations rather than causal evidence. LCR = Leaf Coverage Ratio; DI = Defoliation Index; RMedian = red-channel median.

Specifically, Tmean was strongly consistent with Tmin and Tmax, while RHmean was closely associated with RHmin and RHmax, indicating that mean temperature and humidity backgrounds were jointly shaped by intra-day upper and lower bounds. Tmin, Tmax, and Tmean were positively correlated with LCR and negatively correlated with DI, suggesting that higher temperature backgrounds corresponded to greater leaf retention and lower defoliation intensity. RHmean was negatively correlated with DI and positively correlated with LCR and Color Index, suggesting that the humidity background was also related to leaf decline and color change. By contrast, ΔT and ΔRH showed relatively weak associations with most image-derived phenological indicators, suggesting that autumn façade-greening dynamics could not be explained by a single thermal–humidity fluctuation indicator alone.

The internal relationships among phenological indicators further show that leaf color and defoliation are related but asynchronous. LCR was strongly negatively correlated with DI, LCR was positively correlated with RMedian, RMedian was strongly positively correlated with Color Index, and DI was negatively correlated with both RMedian and Color Index. These relationships indicate that color composition, leaf retention, and defoliation jointly constitute the autumn phenological process. Autumn plant processes cannot be explained by a single temperature–humidity fluctuation indicator; radiation exposure, ventilation conditions, and temporal accumulation, which were not directly included in the present statistical model, may also contribute to phenological differences among sample points.

For this reason, this study does not use a single image indicator to represent the entire autumn process. Instead, it analyzes RMedian and Color Index, which represent the color dimension, alongside LCR and DI, which represent the structural dimension. This combined approach captures both pigment-related visual change and the quantitative reduction in façade leaf cover, thereby avoiding the misinterpretation of complex landscape change as a simple linear decline.

3.4. The Role of Architectural Micro-Spaces Under a Shared Seasonal Background

The preceding correlation analysis demonstrates that microclimate and phenology are linked, but this linkage cannot be reduced to a simple hierarchy of enclosure types. Figure 8 shows that Boston ivy in all enclosure types exhibited leaf color change and declining leaf coverage under the shared seasonal background, indicating that the regional seasonal process constituted the fundamental driver of autumn phenology. However, DI and Color Index changed over time in all enclosure types without forming persistent,

stable, and fully separated group trajectories. Therefore, the rhythm of autumn phenology cannot be attributed to building enclosure form alone. Instead, enclosure form should be interpreted together with façade orientation, near-wall thermal–humidity conditions, and temporal accumulation when explaining the progression of autumnal changes in façade greening.

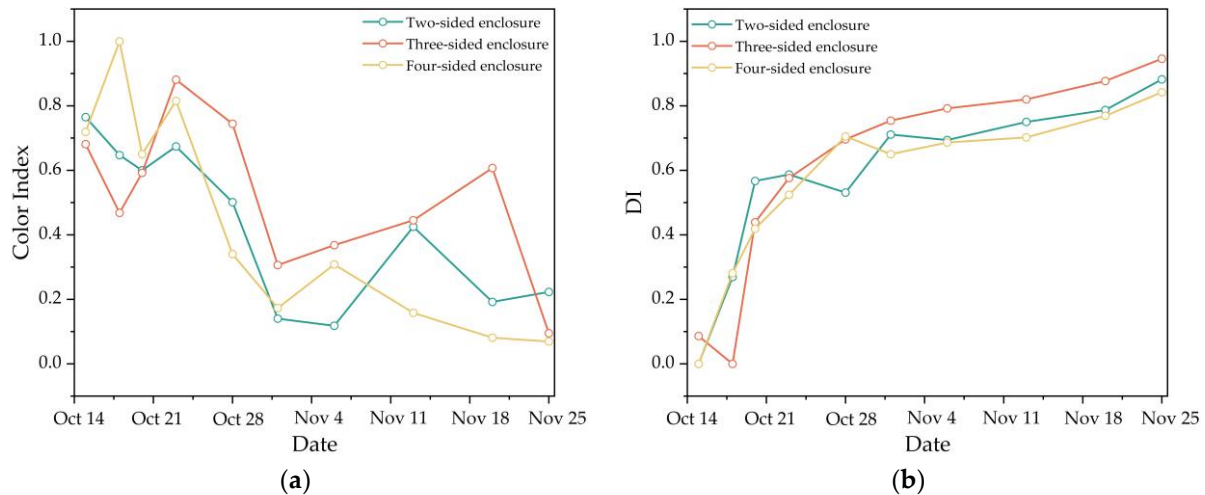


Figure 8. Time-series trajectories of phenological indices: (a) Defoliation Index by enclosure type; (b) Color Index by enclosure type.

Taken together, Figure 8 and the analysis of key phenological dates show that DI and Color Index primarily describe the relative pace of phenological progression, while the overlap among enclosure-type trajectories indicates that sample differences cannot be simply assigned to a graded sequence of two-sided, three-sided, and four-sided enclosure. This finding is consistent with the preceding differences in key phenological dates: architectural micro-spaces were associated with differences in the onset, progression rate, and stage structure of defoliation and coloration, but these differences should not be interpreted as linear or deterministic enclosure effects.

3.5. Phenological Differences Among Orientations Under the Same Enclosure Form

To examine whether façade orientation was associated with differences in autumn phenology under the same enclosure condition, this study compared the time series of DI and Color Index between Sample 1 (south-facing) and Sample 2 (west-facing) in two-sided enclosed spaces, and between Sample 3 (south-facing) and Sample 4 (north-facing) in four-sided enclosed spaces. Because both three-sided enclosure sites were north-facing, the present dataset does not permit an orientation comparison within the three-sided category. This section therefore focuses on the two-sided and four-sided categories, in which different façade orientations were represented within the same enclosure-form category. These within-category comparisons partially control for enclosure form and are used to examine orientation-related phenological differences. However, they do not isolate façade orientation as an independent factor because each orientation was represented by a different monitoring site and other site-specific exposure conditions were not fully controlled.

Figure 9 compares the DI and Color Index trajectories of sample points with different orientations under the same enclosure form. The results show that even when enclosure degree was identical, sample points with different orientations still differ in the onset of leaf-cover decline, progression rate, and timing of the leaf-color peak. These results suggest that façade orientation should be considered together with enclosure form when interpreting phenological temporal structure within architectural micro-spaces.

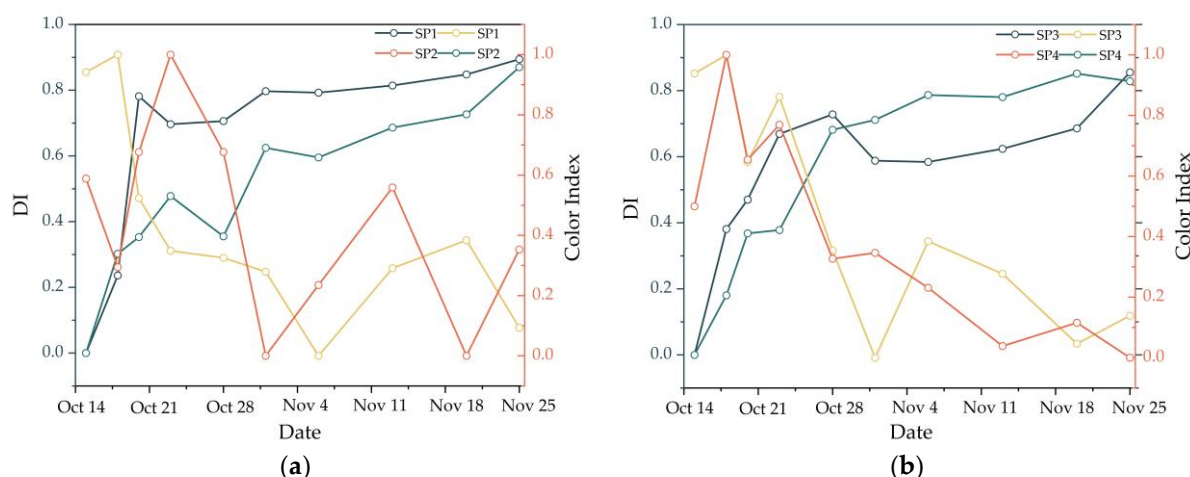


Figure 9. Comparison of DI and Color Index trajectories under the same enclosure type but different façade orientations: (a) SP1 and SP2 under two-sided enclosure; (b) SP3 and SP4 under four-sided enclosure.

Under two-sided enclosure, sample point 1 defoliated rapidly and reached its leaf-color peak early, while sample point 2 defoliated more slowly, peaked later, and showed greater late-stage fluctuation. Under four-sided enclosure, sample points 3 and 4 both began defoliating in the early period, but their rhythms differed: sample point 3 exhibited slower late-stage color decline; whereas, sample point 4 declined more completely. These results suggest that enclosure form provides the broader spatial context, while façade orientation may contribute to differentiated phenological temporal structures through differences in exposure and near-wall thermal-humidity conditions.

4. Discussion

4.1. Near-Wall Microclimate and Autumn Phenology Across Courtyard Enclosure Forms and Façade Orientations

The results can be interpreted through two related but distinct relationships. The first concerns how combinations of courtyard enclosure form and façade orientation were associated with measured near-wall thermal-humidity conditions. The second concerns how these measured conditions were associated with image-derived indicators of autumn leaf coloration and defoliation. Distinguishing these relationships is necessary because the present study identifies associations among spatial conditions, measured environmental indicators, and phenological processes, but does not establish a complete causal pathway.

For the first relationship, daily mean temperature varied from 4.04 ± 4.97 °C at SP1 to 5.60 ± 5.00 °C at SP3, while daily mean relative humidity ranged from $46.45 \pm 11.87\%$ at SP2 to $54.52 \pm 10.34\%$ at SP6. By contrast, ΔT ranged from 8.79 ± 2.35 °C at SP6 to 17.90 ± 7.21 °C at SP2, and ΔRH ranged from $18.46 \pm 4.59\%$ at SP6 to $29.81 \pm 7.38\%$ at SP2. These results show that the monitored sample points differed more clearly in diurnal thermal-humidity fluctuation than in mean conditions.

Comparable case studies provide a useful basis for interpreting these patterns. Rodríguez-Algeciras et al. [19] showed that courtyard aspect ratio and orientation produced substantial differences in the spatial and temporal distribution of mean radiant temperature in warm-humid courtyards. In a winter-cold courtyard-style architectural ensemble, Lin and Gui [30] similarly found that the internal microclimate varied with the overall spatial organization of the courtyard ensemble, including its aspect-ratio conditions. At the building-vegetation interface, Zhao et al. [32] further demonstrated that the microclimatic performance of vegetated façades varied among isolated buildings, street canyons, and building arrays. Taken together, these cases support the interpretation that

courtyard and façade-greening performance is conditioned by interacting geometric and exposure variables rather than by a single formal category. The present study extends this comparison to autumn near-wall conditions: unlike previous studies centered mainly on summer thermal comfort or simulated thermal performance, the monitored settings were differentiated more clearly by ΔT and ΔRH than by T_{mean} and RH_{mean} . This pattern suggests that the monitored enclosure–orientation settings were associated more clearly with near-wall environmental variability than with persistent differences in mean conditions. However, the underlying radiation, airflow, and surface-temperature processes were not directly measured. Because the climatic contexts, response variables, and analytical methods differ, these comparisons are qualitative and should not be treated as direct numerical benchmarks.

For the second relationship, the correlation analysis showed that mean temperature indicators were positively associated with LCR and negatively associated with DI, while RH_{mean} was associated with leaf retention, defoliation, and color change. By contrast, ΔT and ΔRH showed weaker relationships with most image-derived indicators. The measured thermal–humidity background was therefore related to autumn phenological progression, but no single thermal–humidity indicator adequately explained the observed color and leaf-cover changes. Because the analysis was based on repeated and temporally ordered observations, these correlations should be interpreted as exploratory contemporaneous associations rather than causal effects or confirmed lagged responses.

Because all sample points shared the same plant species and regional seasonal background, species-level and broad seasonal variation was reduced, although site-specific differences could not be excluded. The observed differences may reflect the combined influence of enclosure form, façade orientation, and other site-specific exposure conditions. Radiation access, ventilation, shading, wall-surface temperature, and moisture availability are plausible pathways through which these spatial configurations could modify the environment experienced by façade vegetation. However, these variables were not directly monitored and should therefore be regarded as potential explanatory mechanisms rather than empirically demonstrated pathways. The present study directly documents differences in the measured near-wall thermal–humidity conditions and identifies exploratory associations between these conditions and image-derived phenological indicators.

Taken together, the evidence supports two empirical linkages: combinations of enclosure form and façade orientation were associated with near-wall thermal–humidity conditions, and these measured conditions were associated with specific dimensions of autumn phenology. Neither linkage should be interpreted as proof of an independent enclosure-form effect or as a complete mechanistic explanation.

4.2. Asynchrony Between Leaf Coloration and Defoliation

Recent research on autumn phenology has shifted from focusing solely on leaf-fall timing to examining the mechanisms underlying the entire senescence process [7,33,34]. Studies indicate that under a warming climate, leaf senescence does not follow a simple linear response, but is jointly regulated by multiple factors, including temperature, photoperiod, photosynthetic productivity, and physiological constraints. Meanwhile, local microclimates not only influence the timing of leaf abscission but also modify the onset and duration of color change. Rather than simplifying autumn phenology to a single temporal point, this study characterizes the full temporal dynamics of façade vegetation senescence using multiple process-based indicators, including leaf-color peak date (R_{Peak}), Leaf Coverage Ratio (LCR), Defoliation Index (DI), DI50, DI80, and the duration of each stage. These indicators provide a time-series depiction of autumnal decline.

The key-date statistics in Table 3 provide direct evidence that autumn façade-greening dynamics cannot be reduced to a single phenological event. R_{Peak} , DI50, and DI80

occurred on different dates across sample points. SP1 and SP6 reached DI50 earliest on 20 October 2025; whereas, SP2 reached DI50 the latest, on 1 November 2025. SP6 reached DI80 earliest on 6 November 2025, while SP2 and SP3 reached DI80 the latest, on 25 November 2025. The duration of Stage II ranged from 17 days at SP6 to 33 days at SP3, indicating different rates of transition from mid-stage to near-complete defoliation.

These differences show that autumn phenology in façade greening is not a linear decline from coloration to defoliation. Rather, it is a coupled and composite dynamic between color processes and structural processes. This finding strengthens the urban-design relevance of the study: the seasonal performance of façade greening cannot be evaluated only by whether plants survive or whether they provide summer cooling. It also depends on the timing, duration, and synchrony of leaf color change, leaf retention, and defoliation.

The correlation results in Table 4 further support this interpretation. LCR was strongly and negatively correlated with DI ($\rho = -0.77$, $p < 0.001$), while RMedian was strongly and positively correlated with Color Index ($\rho = 0.75$, $p < 0.001$). DI was negatively correlated with RMedian and Color Index ($\rho = -0.50$ and -0.53 , respectively; $p < 0.001$). These relationships indicate that leaf-cover decline and leaf color change were related but not identical processes.

The core methodological implication is that autumn façade-greening dynamics should be represented by both color-related and structure-related indicators, rather than by a single phenological date. The color dimension is represented by RMedian and Color Index, while the structural dimension is represented by LCR and DI. This interpretation is consistent with image-based phenological monitoring studies, which show that fixed cameras, time-series imagery, and color-channel metrics can be used to characterize seasonal vegetation dynamics [22–24].

One result requires cautious interpretation. SP5 showed a substantially later RPeak than the other sample points. This may indicate delayed color intensification under the local north-facing three-sided condition. However, late-stage RMedian can also be influenced by reduced leaf-pixel numbers, illumination conditions, and residual leaves. Therefore, the RPeak of SP5 should be interpreted as a relative image-based peak within the fixed-ROI time series rather than as an absolute physiological peak of the whole plant.

4.3. Joint Interpretation of Enclosure Form and Façade Orientation

The architectural scale remains important because façade vegetation does not experience a uniform urban climate. Existing studies on urban plant phenology have shown that plant seasonal rhythms are affected not only by broad urban–rural gradients, but also by local thermal environments, land-surface conditions, local climate zones, canopy structure, light availability, and plant functional traits [5,7,33,34]. In dense urban environments, microclimatic differences are shaped not only by streets or neighborhoods, but also by smaller architectural spaces where enclosure form, orientation, openings, shading, and wall surfaces reorganize radiation, airflow, and heat–moisture exchange [1,16,17,30]. Boston ivy growing on façades therefore responds to a specific near-wall environment rather than to the regional climate background alone.

However, the present results should not be interpreted as demonstrating a simple hierarchy among enclosure forms. The trajectories of DI and Color Index did not form a consistent sequence from two-sided to three-sided and four-sided spaces, and the timing of RPeak, DI50, and DI80 also varied within and across enclosure-form categories. The within-category comparisons in Section 3.5 further showed that sample points classified under the same enclosure form did not necessarily follow identical phenological trajectories.

Under two-sided enclosure, SP1 reached DI50 on 20 October 2025; whereas, SP2 reached DI50 on 1 November 2025. Under four-sided enclosure, SP3 and SP4 reached DI50 on 23 and 28 October 2025, respectively. These contrasts indicate orientation-related differences within the same enclosure-form category. However, they cannot be interpreted as isolating an independent façade-orientation effect, because each orientation was represented by a different sample point and other site-specific exposure conditions were not fully controlled. No corresponding orientation comparison was possible within the three-sided category because both SP5 and SP6 were north-facing. A closely related field case is provided by Susorova et al. [10], who monitored bare and ivy-covered façades on four orientations of university buildings and found that the effects of climbing vegetation on façade surface temperature, near-wall air conditions, and air velocity varied with orientation and time of day. Zhao et al. [32] likewise showed that the microclimatic performance of vegetated façades changed across different surrounding building morphologies. These findings are consistent with the present within-enclosure comparisons, in which south-, west-, and north-facing sample points followed different phenological trajectories. However, the previous studies focused primarily on summer thermal and microclimatic performance; whereas, the present study concerns autumn coloration and defoliation. Moreover, each orientation in the present dataset was represented by a different monitoring site. The comparison therefore supports the relevance of façade orientation and built-form context but does not justify a causal ranking of façade orientations.

The microclimate–phenology associations should be interpreted within the same methodological boundary. Mean thermal–humidity indicators showed more consistent associations with LCR, DI, and color-related indicators than did ΔT and ΔRH , but these correlations were derived from repeated observations across sample points representing different combinations of enclosure form and façade orientation. They therefore describe exploratory associations within the monitored configurations rather than independent responses attributable to either enclosure form or façade orientation.

The core finding is therefore not that Boston ivy becomes redder or defoliates faster in a particular enclosure type. Rather, the results indicate that architectural micro-spaces can help explain differences in the temporal structure of seasonal façade-greening performance under a shared seasonal background. Given the partial confounding between enclosure form and façade orientation in the current dataset, these differences should not be interpreted as independent enclosure-form effects. Enclosure form is better understood as a moderating spatial condition that operates together with façade orientation, exposure conditions, and near-wall thermal–humidity environments to shape the timing and progression of autumn leaf coloration and defoliation.

4.4. Design Implications for Courtyard Façade Greening

From a design perspective, the findings suggest that façade greening should not be evaluated only by summer cooling potential, energy saving, or maximum plant coverage. Previous studies have shown that façade greening can influence building-surface and near-wall microclimates through shading, transpiration, insulation, wind-barrier effects, boundary-layer air exchange, and leaf area index [15,35–37]. For deciduous climbers such as Boston ivy, autumn coloration, leaf retention, and winter defoliation also form part of seasonal landscape performance. Courtyard enclosure, façade orientation, and planting strategy should therefore be considered together when designing façade greening in small architectural spaces.

The results also suggest that design assessment should consider both mean thermal–humidity conditions and the magnitude of diurnal fluctuations. Because ΔT and ΔRH showed clearer differentiation than T_{mean} and RH_{mean} , relying only on mean conditions may overlook important differences in the near-wall environment. However, the present

findings do not support identifying any single enclosure form or façade orientation as universally preferable; design decisions should instead be based on site-specific combinations of enclosure, orientation, and exposure conditions.

The seasonal characteristics of deciduous façade greening can also be used as a design resource. Dense summer foliage can potentially provide shading and evapotranspirative cooling; autumn coloration can contribute to spatial quality and seasonal visual interest; winter defoliation may help restore solar access and daylight [38]. However, based on the exploratory nature of this study, these implications should be understood as design considerations rather than universal design rules. Further studies with more sites, longer monitoring periods, and additional plant species are needed before general design guidelines can be established.

4.5. Limitations and Future Research

This study has several limitations that define the scope of interpretation and indicate specific directions for future research. First, only two sample points were included in each enclosure-form category, and enclosure form and façade orientation were not fully crossed in the sampling design. In particular, both three-sided enclosure sites were north-facing. The observed differences should therefore be interpreted as associations with combined enclosure–orientation settings rather than as independent effects of enclosure form or façade orientation. Future studies should adopt a balanced crossed sampling design in which each enclosure form is represented across the principal façade orientations, with multiple spatial replicates for each enclosure–orientation combination. Plant species, plant age, wall material, irrigation, maintenance, and surrounding surface conditions should also be matched or quantitatively recorded. Such a design would provide a stronger basis for distinguishing the independent and interactive contributions of enclosure form, façade orientation, and site-specific exposure conditions.

Second, continuous environmental monitoring was limited to near-wall air temperature and relative humidity. Although these indicators characterize the thermal–humidity conditions experienced near the façade, they do not fully identify the physical processes through which courtyard spatial configurations may influence plant phenology. Future field campaigns should simultaneously measure solar radiation, including photosynthetically active radiation, near-wall wind speed, wall- and leaf-surface temperatures, and substrate or root-zone temperature and moisture. Quantitative measures of shading duration, sky view factor, and opening characteristics would further help distinguish the potential roles of radiation exposure, thermal storage, ventilation, and plant water availability. Field measurements could also be combined with ENVI-met or CFD simulations, provided that the simulations are calibrated and validated using site-specific observations.

Third, the fixed-ROI image-processing workflow improved temporal comparability but remained sensitive to changes in natural illumination, shadows, camera white balance, declining leaf-pixel numbers, and manual background removal. Because no physical color-calibration reference was used, RMedian and Color Index should be interpreted as relative within-point temporal indicators rather than as absolute color measurements. Future studies should use fixed camera settings, RAW-image acquisition where possible, and color-calibration cards periodically included in the photographed scene. Automated or semi-automated leaf segmentation should be validated against manually labeled images. Image-derived transition dates and defoliation thresholds could also be cross-checked through manual phenological observations, repeated leaf counts, leaf-area measurements, or leaf-level pigment and spectral measurements.

Fourth, the observations covered one plant species, one campus, and one autumn season. In addition, the daily observations were temporally ordered and repeatedly collected from the same sample points. The Spearman correlations reported in this study

therefore represent exploratory contemporaneous associations and do not explicitly account for site-level variation, temporal autocorrelation, or delayed phenological responses. Future studies should extend monitoring across multiple years, campuses, climatic conditions, and deciduous façade-greening species. With a larger and more balanced dataset, mixed-effects or hierarchical models could treat site as a random effect and account for repeated temporal observations, while lagged-response or time-series models could examine whether environmental changes precede changes in leaf coloration or defoliation.

These limitations do not invalidate the present findings, but they restrict the conclusions to exploratory and site-specific associations. The study provides an empirical basis for future replicated and balanced investigations of how courtyard spatial configuration, near-wall environmental conditions, and plant characteristics jointly shape autumn façade-greening phenology.

5. Conclusions

This exploratory field study investigated the autumn phenology of Boston ivy at six façade-greening sample points within a university courtyard. By combining near-wall thermal–humidity monitoring with fixed-ROI time-series imagery, the study examined two related but distinct linkages: how combinations of courtyard enclosure form and façade orientation were associated with near-wall thermal–humidity conditions, and how these measured conditions were associated with leaf coloration and defoliation.

- (1) First, daily mean temperature and relative humidity differed only modestly among the sample points; whereas, daily temperature and relative-humidity ranges showed clearer differentiation. Thus, the monitored combinations of enclosure form and façade orientation were distinguished more clearly by near-wall thermal–humidity variability than by mean conditions.
- (2) Second, the timing and progression of leaf coloration and defoliation varied among the sample points. Differences were observed in RPeak, DI50, DI80, and the duration of Stage II, while peak coloration did not consistently coincide with the decline in leaf coverage. Autumn phenology should therefore be interpreted as a composite process involving both color transition and structural leaf loss rather than as a single synchronous progression.
- (3) Third, the associations between near-wall thermal–humidity indicators and image-derived phenological indicators were selective rather than uniform. Mean temperature and relative humidity were more consistently associated with indicators of leaf retention, defoliation, and color change; whereas, relationships involving diurnal ranges were less consistent. Because the analysis was based on repeated and temporally ordered observations, these relationships represent exploratory contemporaneous associations rather than causal effects or confirmed lagged responses.
- (4) Fourth, the monitored combinations of enclosure form and façade orientation were associated with configuration-specific differences in the temporal structure of autumn phenology. These differences were expressed through shifts in key phenological dates and stage duration rather than through a consistent sequence determined by enclosure form alone. Because enclosure form and façade orientation were not fully crossed in the sampling design, and both three-sided enclosure sites were north-facing, their respective contributions could not be statistically separated. The observed patterns should therefore be interpreted as being associated with combinations of enclosure form, façade orientation, measured near-wall thermal–humidity conditions, and other site-specific exposure factors.

From a design perspective, courtyard façade greening should be evaluated by considering enclosure form and façade orientation together rather than by applying a single

enclosure-based rule. Assessment should also extend beyond mean temperature and humidity to include diurnal thermal–humidity fluctuations and should distinguish seasonal color performance from leaf-retention duration. These implications should be regarded as exploratory design considerations rather than general prescriptions.

The generalizability of the findings is limited by the use of two sample points per enclosure category, one plant species, one campus, and one autumn season. Future studies should employ balanced and replicated combinations of enclosure form and façade orientation across multiple sites and years. Environmental monitoring should also include solar radiation, including photosynthetically active radiation, near-wall wind speed, wall-surface temperature, and substrate moisture, together with mixed-effects or lagged-response models. Such work would provide a stronger basis for distinguishing the roles of spatial configuration, near-wall environmental conditions, and plant characteristics in autumn façade-greening phenology.

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Data Availability Statement: The data supporting the findings of this study, including near-wall temperature–humidity monitoring data and processed image-derived phenological indicators, are available from the corresponding author upon reasonable request. The original time-series images are not publicly available due to file size and site-specific image restrictions.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

CGSD	Color Gradient Skewness Distribution
DI	Defoliation Index
DI50	Date when the Defoliation Index first reached 0.5
DI80	Date when the Defoliation Index first reached 0.8
LCR	Leaf Coverage Ratio
ROI	Region of Interest
RH	Relative Humidity
RHmean	Daily mean relative humidity
Δ RH	Daily relative humidity range
Δ T	Daily temperature range
RMedian	Red-channel median
RPeak	Date of maximum RMedian
SP	Sample Point
Tmean	Daily mean temperature
Tmin	Daily minimum temperature
Tmax	Daily maximum temperature
RHmin	Daily minimum relative humidity
RHmax	Daily maximum relative humidity

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