Landscape and Ecological Engineering
https://doi.org/10.1007/s11355-025-00694-1

ORIGINAL PAPER

Entropy-weighted fuzzy and user perception-based framework for riverside greenway landscape quality assessment

Yingnan Li[1,3] · Zhicheng Zhou[1] · Yuedong Wang[4] · Yakun Chang[1] · Menglin Zhou[1] · Guangxi Shen[5] · Yuhan Zhang[6,7] · Zipeng Song[6,7] · Lu Ding[1,2]

Received: 4 August 2025 / Revised: 17 September 2025 / Accepted: 13 October 2025

Abstract
Urban riverside greenways contribute significantly to ecological resilience, non-motorized mobility, and urban livability. However, comprehensive evaluation methods that integrate quantitative analysis with differentiated user perceptions remain limited. This study developed a combined entropy-weighted fuzzy evaluation and user perception framework to assess the landscape quality of the Zhenjiang riverside greenway, a site frequently visited by residents and tourists. A hierarchical indicator system was established with three dimensions: functional facilities, visual landscape, and cultural connotation, and 28 evaluation indicators reflecting the multidimensional attributes of greenway landscape quality. Indicator weights were determined using the entropy weight method, and fuzzy comprehensive evaluation was employed to quantify landscape performance along the greenway. Structured perception surveys were conducted with residents and tourists to assess their perceptions. The results indicated that visual landscape accounted for the highest importance (5.80), followed by functional facilities (4.07) and cultural connotation (3.87). Furthermore, there were significant differences in the landscape quality of sample spots; those with higher vegetation coverage, better accessibility, and complete facilities exhibited better evaluation performance. Due to the different demands of residents and tourists, the difference in perception scores for the same spot reached up to 1.11. Hence, this study demonstrated the effectiveness of integrating entropy-weighted fuzzy evaluation with user perception differentiation, supporting evidence-based and inclusive greenway planning. The proposed framework is a practical and transferable tool for efficiently and scientifically assessing urban riverside greenways.

Keywords Ecological resilience · Non-motorized mobility · Urban livability · Landscape performance · Perception surveys · Greenway planning

Zhicheng Zhou is the co-first author of this paper.

✉ Lu Ding
ding241@purdue.edu

1 Department of Environmental Design, Jiangsu University, Zhenjiang 212013, China

2 Department of Computer Graphics Technology, Purdue University, West Lafayette 47907, USA

3 OJEong Resilience Institute, Korea University, Seoul 02841, Republic of Korea

4 Department of Environmental Science and Ecological Engineering, Korea University, Seoul 02841, Republic of Korea

5 School of Landscape Architecture, Lincoln University, Christchurch 7647, New Zealand

6 Interdisciplinary Program in Landscape Architecture, Seoul National University, Seoul 08826, Republic of Korea

7 Integrated Major in Smart City Global Convergence Program, Seoul National University, Seoul 08826, South Korea

Published online: 06 January 2026

Abbreviations

GIS	Geographic information system
PPGIS	Public Participation GIS
OSM	OpenStreetMap
EWM	Entropy weight method
FCE	Fuzzy comprehensive evaluation
EWFCE	Entropy-weighted fuzzy comprehensive evaluation

Introduction

Urban riverside greenways are critical to blue-green infrastructure, offering ecological, social, and recreational benefits within urban environments (Herath and Bai 2024a, b). As linear green corridors, they improve urban air quality, enhance biodiversity, mitigate heat island effects, and contribute to climate resilience (Wang et al. 2021, 2024; Rezaei et al. 2024). Additionally, they support active transportation by providing safe and attractive walking and cycling routes while offering spaces for leisure, cultural activities, and social interactions to strengthen community ties (Walmsley 1995; Stroope 2021; Zawawi et al. 2023). However, rapid urbanization has led to the canalization and hardening of urban rivers, reducing their ecological functions and aesthetic appeal while fragmenting natural landscapes (Chester and Robson 2013; Palmer et al. 2014).

Canalized urban rivers, characterized by concrete embankments and limited vegetation, frequently result in poor visual organization and diminished user experiences (Li et al. 2022). Recognizing the multifunctional value of riverside greenways, cities worldwide are increasingly transforming these corridors into vibrant, accessible, and ecologically functional spaces that support sustainable urban development (Wolch et al. 2014; Fang et al. 2023). The success of these initiatives depends largely on the landscape quality of the greenways, which directly influences ecological performance, user satisfaction, and the capacity of these spaces to deliver environmental and social benefits in rapidly urbanizing contexts.

Assessing the landscape quality of riverside greenways is essential for sustainable urban planning and management, as it informs design interventions, policy decisions, and maintenance strategies for enhancing ecological performance and user experiences (Ahern 2013; Carlier and Moran 2019). Traditional assessments have primarily focused on objective indicators, such as vegetation cover, spatial connectivity, accessibility, and aesthetic composition, using spatial metrics, remote sensing data, and field measurements to quantify greenway conditions and performance (Carlier and Moran 2019; Liu et al. 2024). While these objective measures are valuable for evaluating ecological and functional attributes, they overlook the perceptual and experiential dimensions of landscape quality, such as users' comfort, safety, visual appeal, and emotional connection to the space (Brown and Raymond 2007).

These subjective dimensions are critical, as they directly influence how people interact with greenway environments, affect the frequency and duration of their use, and contribute to the perceived value and acceptance of green infrastructure interventions within urban communities (Kabisch and Haase 2014). Moreover, landscape quality assessments that fail to capture user-centered perspectives overlook important barriers to inclusivity and accessibility, which can disproportionately affect vulnerable populations, including the elderly, children, and people with disabilities (Kabisch and Haase 2014; Wolch et al. 2014; Rigolon 2016). Without integrating these experiential and perceptual factors, assessment frameworks provide an incomplete understanding of greenway performance. This reduces their effectiveness in creating riverside green spaces that are ecologically resilient, socially inclusive, engaging, and responsive to the diverse urban needs.

Recent studies have applied visual landscape assessments, ecological evaluations, and multi-criteria decision analysis frameworks to measure greenway quality across diverse contexts (Balta and Yenil 2019). Additionally, computer vision and geospatial analysis techniques have been employed to quantify multilevel visual characteristics, vegetation structure, and spatial patterns of urban greenways, illustrating how they influence ecological functions and thermal comfort (Zheng et al. 2024b). Liu et al. (2024) used geospatial analysis and recreational mobility data to evaluate landscape connectivity and ecological benefits of urban greenways, demonstrating how linear green corridors shape user flow and support ecosystem services in densely built environments (Liu et al. 2024). Lee et al. (2019a, b). investigated user preferences regarding trail characteristics, including vegetation amount, water presence, trail width, and amenities, in urban greenway environments, highlighting the significant role of vegetation structure and scenic water features in shaping user satisfaction and perceived thermal comfort.

Additionally, some studies have incorporated user surveys and Public Participation Geographic Information System (PPGIS) methods to capture public perceptions of green spaces, emphasizing aesthetic experiences, perceived safety, and recreational satisfaction (Brown and Kyttä 2014). This emerging focus on user-centered perspectives reflects the growing recognition of aligning greenway design and management with user needs and expectations to enhance usage rates, well-being, and social benefits (Cohen et al. 2016). However, few studies have systematically integrated user perception data with quantitative, multi-indicator evaluation frameworks capable of addressing the inherent uncertainty and subjectivity in landscape quality assessments. Consequently, there is a methodological gap in developing comprehensive frameworks that combine objective ecological and spatial data with subjective user experiences to holistically evaluate greenway landscape quality and inform inclusive, user-responsive green infrastructure planning.

User perception offers valuable qualitative insights for such evaluations; however, it is subjective and often inconsistent across individuals and contexts, reflecting differences in cultural backgrounds, personal experiences, and situational factors (Sevenant and Antrop 2010). Conversely, quantitative methods using multi-criteria evaluation frameworks struggle to accommodate the uncertainty and relative importance of diverse indicators, particularly when balancing ecological functions with user-centered experiences in greenway planning (Belton and Stewart 2012). However, entropy-weighted methods objectively determine the significance of various indicators based on data variability, reducing the influence of subjective bias in weighting processes (Gorgij and Moayeri 2023). Meanwhile, fuzzy comprehensive evaluation handles the inherent vagueness and uncertainty in landscape quality assessments, allowing for the inclusion of linguistic variables and imprecise data often encountered when translating qualitative user perceptions into quantitative assessments (Wang et al. 2009).

Hence, combining these methods with user perception data can generate comprehensive, balanced, and practical evaluations of greenway landscape quality by integrating objective ecological and spatial metrics with subjective experiential dimensions (Jim and Chen 2006). Such integrated frameworks facilitate a deeper understanding of how physical attributes, ecological functions, and user experiences intersect within urban riverside greenways, providing planners and policymakers with actionable insights to design and manage greenway spaces that are ecologically resilient, socially inclusive, and responsive to diverse community needs (Gehl and Svarre 2013; Wolch et al. 2014). Nonetheless, there remains a lack of practical applications and tested frameworks that systematically operationalize this integration within greenway landscape quality assessment, indicating the need for innovative approaches to advance the field.

This study developed and applied a combined entropy-weighted fuzzy evaluation and user perception framework for assessing the landscape quality of urban riverside greenways. By systematically integrating objective ecological and spatial indicators with subjective user perceptions, the proposed framework provided a transferable and practical tool to support evidence-based greenway planning and management across diverse urban contexts. To demonstrate the feasibility and effectiveness of the proposed framework, a case study was conducted on a representative riverside greenway in Zhenjiang, a rapidly urbanizing city in eastern China, characterized by a humid subtropical climate, significant industrial and residential development, and a growing emphasis on sustainable urban transformation. Specifically, it achieved the following objectives:

(1) Establish a comprehensive indicator system that incorporates functional facilities, visual landscape, and cultural connotation dimensions relevant to greenway landscape quality
(2) Apply entropy-weighted fuzzy comprehensive evaluation (EWFCE) methods to address the uncertainty and complexity inherent in multi-indicator assessments while balancing the relative importance of diverse indicators
(3) Examine how integrating user perception data with quantitative evaluation methods enhances the understanding of greenway performance and informs user-centered design strategies.

Materials and methods

Study area

Zhenjiang (31.37°-32.19° N, 118.58°-119.58° E) is a mid-sized city located in Jiangsu Province, eastern China, along the southern bank of the Yangtze River (Fig. 1a). The city is characterized by a humid subtropical climate with four distinct seasons, supporting diverse vegetation conducive to urban green space development (Song et al. 2024; Li et al. 2025). In recent years, Zhenjiang has improved its urban livability and environmental quality by developing green infrastructure that provides ecological services, recreational opportunities, and scenic value for residents and visitors.

The studied riverside greenway, situated along the Yangtze River, was developed as an integrated ecological, recreational, and scenic corridor, providing spaces for walking, cycling, and riverfront leisure activities. The greenway extends approximately 8.2 km along the river (Fig. 1b), with a width of 4–6 m. It comprises a dual-path system, with a cycling lane and a pedestrian path of approximately 2–3 m (width) each, which may run parallel or be separated depending on the section. The greenway connects various parks, residential areas, and cultural sites along the river, offering residents and visitors opportunities to engage in walking, jogging, cycling, and enjoying riverfront views (Fig. 1c). It is a key component of the city's green infrastructure network, supporting biodiversity, enhancing microclimatic conditions, and promoting healthy lifestyles

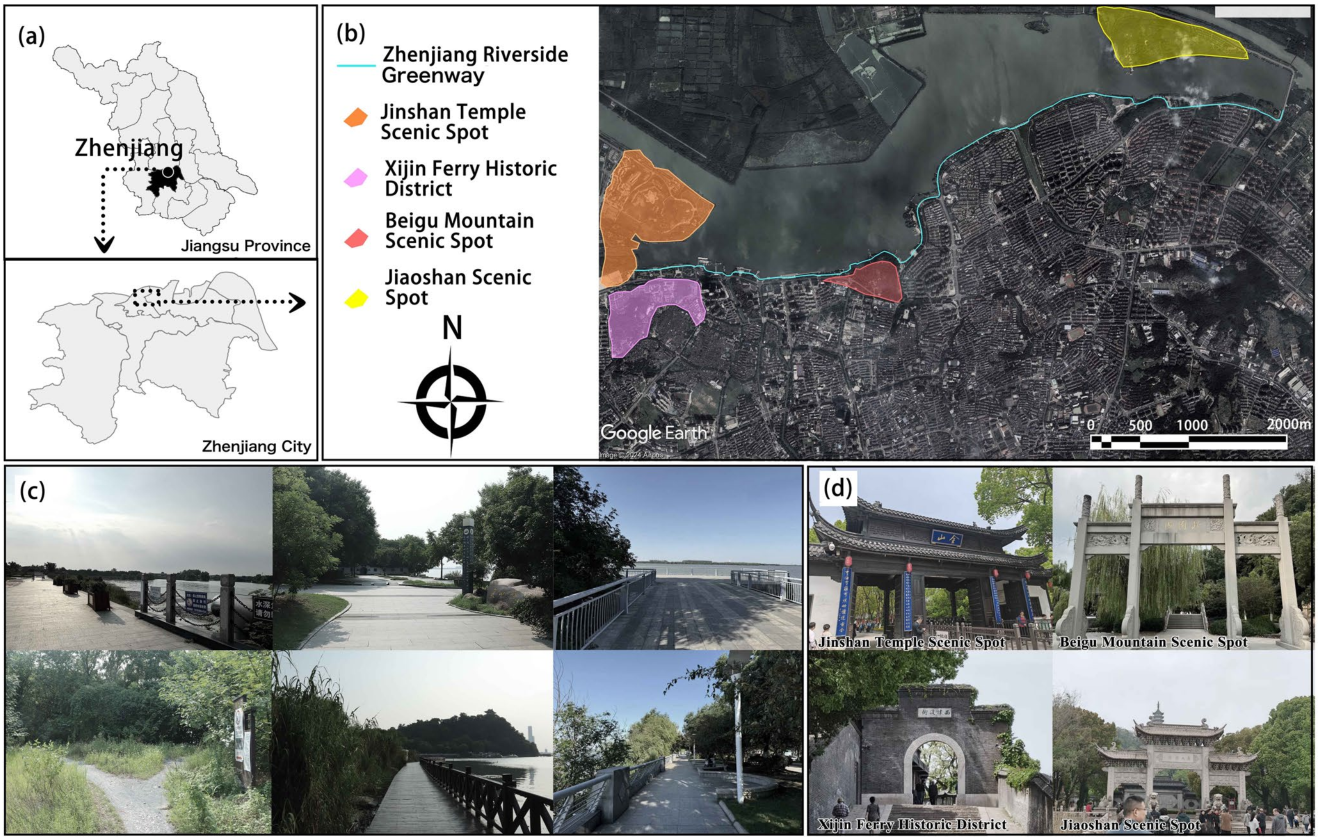

Fig. 1 Site area map: **a** the location of Zhenjiang City; **b** riverside greenway in Zhenjiang; **c** site condition; **d** major tourist attractions near the riverside greenway

while providing a scenic and accessible riverfront for the community.

Framework

This study adopted an integrated evaluation framework that combined objective indicators and user perceptions to comprehensively assess the landscape quality of urban riverside greenways. The framework was structured into five main steps. First, a comprehensive indicator system was developed, incorporating functional facilities, visual landscape, and cultural connotation dimensions relevant to greenway landscape quality. Second, data was collected by obtaining environmental and spatial data through remote sensing, GIS analysis, and on-site measurements, alongside user perception data through structured questionnaires distributed to residents and visitors. Third, the entropy weighting method was applied to calculate the objective weights of the selected indicators, reducing the subjectivity commonly associated with traditional weighting methods.

Fourth, a fuzzy comprehensive evaluation was conducted to integrate the multi-indicator data, addressing the inherent uncertainty and fuzziness in landscape quality assessments while generating composite scores for different greenway segments. Fifth, the evaluation results were visualized spatially using GIS tools to analyze the spatial distribution patterns of landscape quality along the greenway and identify high- and low-quality segments for targeted improvement. This integrated framework provided a transferable and systematic approach for assessing and managing riverside greenway quality, supporting data-driven urban green infrastructure planning and user-centered design. The methodological workflow is illustrated in Fig. 2.

Indicator system and data collection

A targeted indicator system was established to evaluate the landscape quality of the riverside greenway, focusing on spatial characteristics and user perception directly relevant to the study objectives. The spatial dimension included general traffic accessibility, slow-mobility accessibility, segment length, segment width, connectivity, and adjacent land use type, capturing the greenway's physical attributes and its integration with the surrounding urban fabric (Zheng et al. 2024a; Creed and Carvalho 2024). The experiential dimension focused on user perceptions about aesthetic quality, safety, comfort, and overall satisfaction, providing insights into how users experience the greenway environment daily.

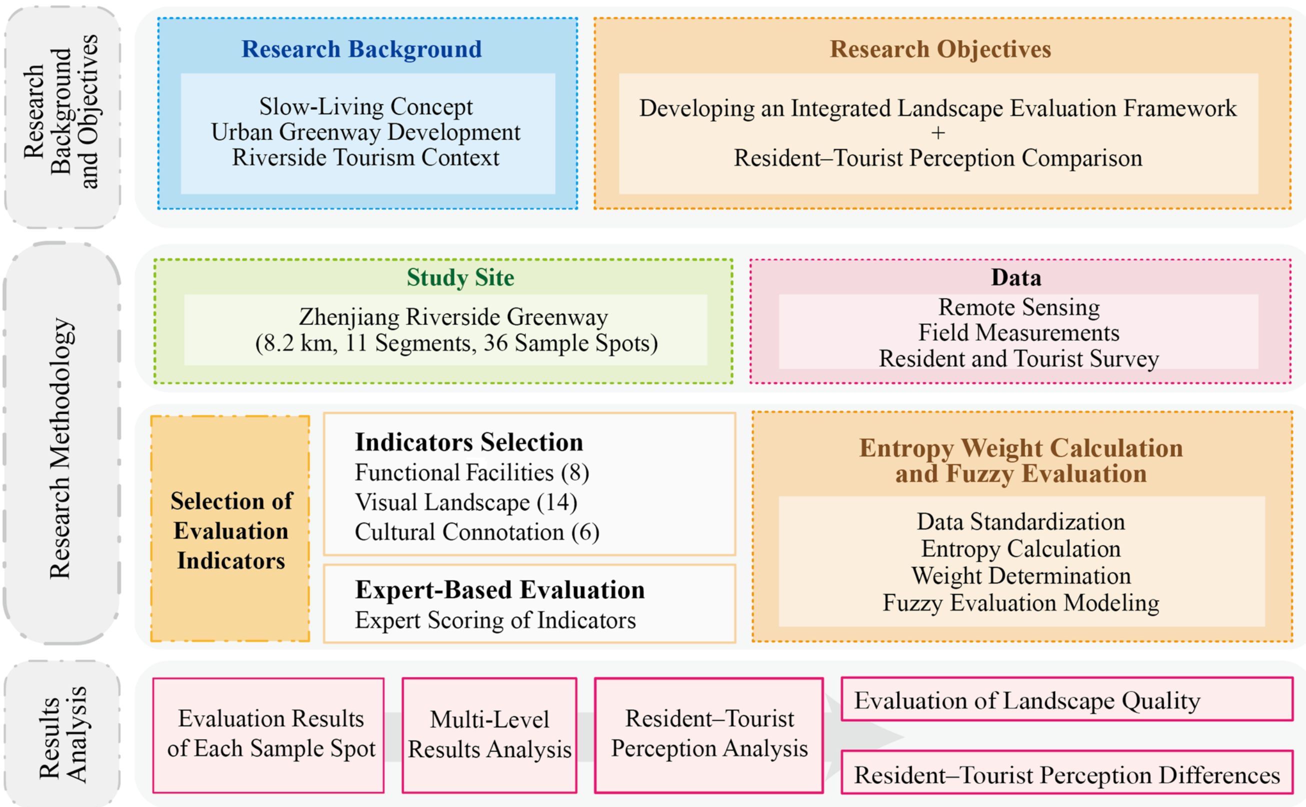

Fig. 2 Study framework

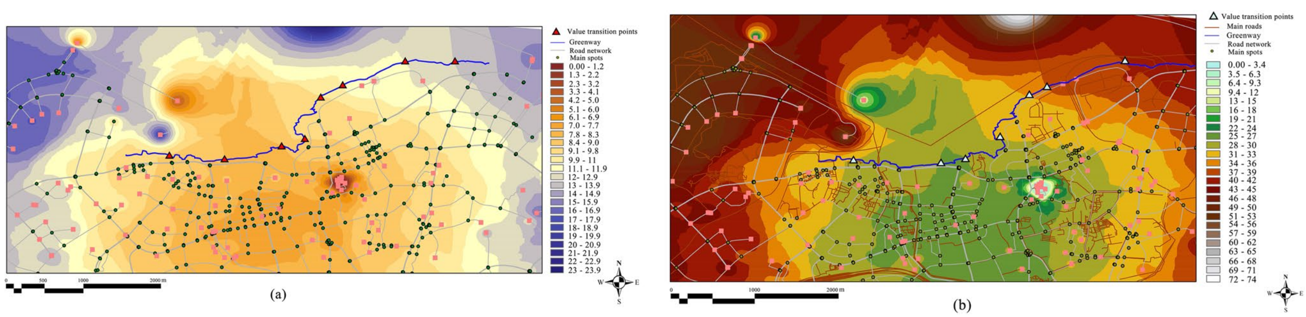

Fig. 3 Classification of road segments based on accessibility. **a** general traffic roads and **b** slow mobility roads

Accessibility analysis and segment division

To systematically prepare the evaluation units, accessibility and segment division analyses were conducted using GIS network analysis (Yuan et al. 2023). The existing transportation network in Zhenjiang was verified using Google aerial imagery, and primary and residential-level roads were systematically processed to ensure accuracy. The road network was categorized into four hierarchical levels—expressways, primary roads, secondary roads, and branch roads—and modeled based on road centerlines with attributes, including traffic speed, travel time, classification, and length, to establish a topological network.

Road network and administrative boundary data for the main urban area were obtained from OpenStreetMap (OSM). Two accessibility scenarios were established: general traffic accessibility (motor vehicles at 30–40 km/h) and slow-traffic accessibility (pedestrians and non-motorized vehicles at 5–15 km/h). Using GIS network analysis, accessibility indices and service areas under both scenarios were calculated, and the results were mapped to illustrate connectivity patterns along the greenway (Fig. 3). Based on the variation in accessibility values, the greenway was divided into segments for further analysis.

Additionally, the spatial data corresponding to the evaluation indicators were collected to support the entropy weight calculation and fuzzy comprehensive evaluation.

Segment length and width were measured through field surveys, while connectivity and adjacent land use types were derived using GIS spatial analysis. The accessibility data obtained from the network analysis were integrated with these datasets, ensuring the comprehensive spatial characterization of the greenway for multi-criteria landscape quality evaluation.

Furthermore, a kernel density analysis of building distributions was conducted to assess the spatial concentration of urban development and its potential influence on greenway accessibility and user demand (Fig. 4) (Yang et al. 2019). The results were integrated with the accessibility analysis to inform the segmentation of the riverside greenway, resulting in segment divisions.

Segmentation of the riverside greenway and selection of sample spots

Based on the combined results of accessibility and residential building density analyses, overlapping value transition points were identified and used to determine the final segmentation points. This resulted in the division of the riverside greenway into 11 segments, with boundaries delineated based on nearby representative buildings or landmarks. Details of these segments, including their lengths and contextual characteristics, are provided in Table 1 and Fig. 5. To comprehensively capture the spatial characteristics of the riverside greenway, the 8.2-km route was sampled at 50-m intervals, resulting in 82 measurement points, evenly distributed across the 11 segments.

Considering the practical constraints of conducting the EWFCE, 36 representative sample spots were proportionally selected from the 82 points to ensure feasibility while maintaining spatial representativeness. The selection considered segment length, general traffic accessibility, slow-mobility accessibility, and residential building density to reflect varying segment characteristics. Detailed data on each segment and the proportional allocation of sample spots are provided in Table 2. The final spatial distribution of the 36 sample spots across the 11 segments is presented in Fig. 5.

Development of landscape quality evaluation indicators and weighting

Selection of evaluation indicators

To comprehensively assess the landscape quality of the riverside greenway, this study developed a structured indicator framework informed by user behavior and needs, landscape aesthetics theory, and the intrinsic attributes of the greenway. A total of 28 evaluation indicators were selected across three dimensions: functional facilities, visual landscape, and cultural connotation. These indicators were organized into a hierarchical structure comprising the goal layer, criteria layer, sub-criteria layer, and indicator layer to guide systematic and replicable evaluation (Li et al. 2018; Yang et al. 2019; Shen et al. 2022). The detailed structure of the evaluation indicators is presented in Table 3, while the definitions, attributes, and data sources of each indicator are summarized in Table A1 in the appendix.

To accurately determine the relative importance of these indicators, an expert-based scoring approach was employed. Given the specificity of the selected indicators, which reflected the contextual characteristics of the riverside greenway and user demands, relevant social network data

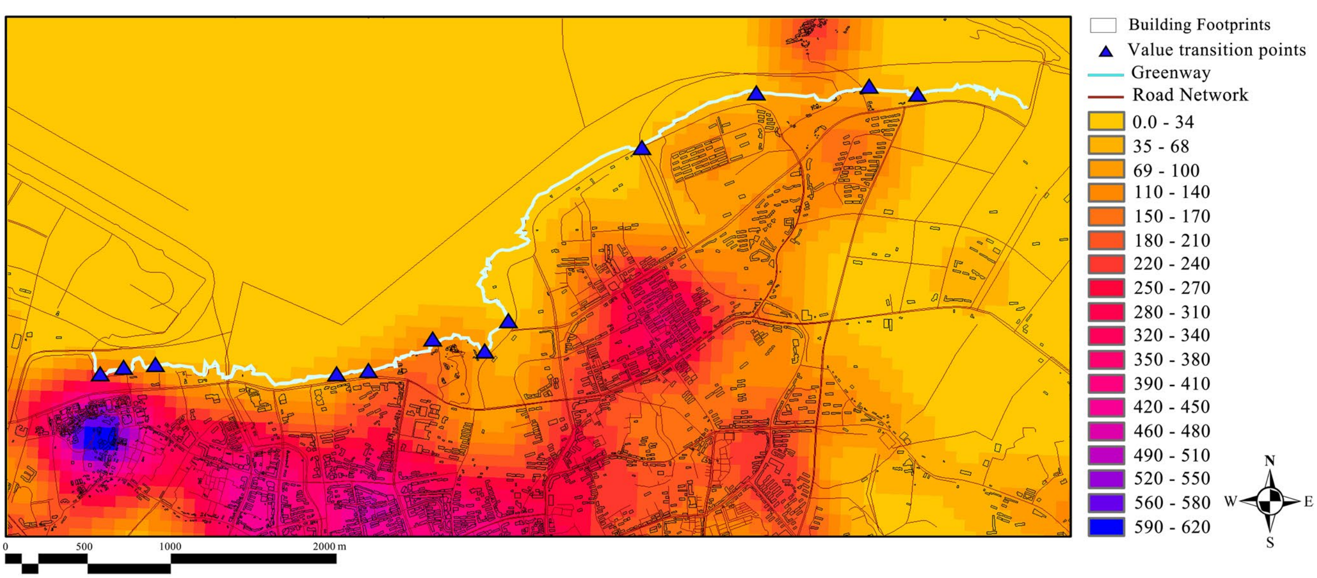

Fig. 4 Residential building density and accessibility-based segmentation of the riverside greenway in Zhenjiang

Table 1 Features of riverside greenway segments

No.	Description	Typical View
a.	Western starting section of the greenway near a historic riverside wharf area, transitioning from traditional residential surroundings toward the riverside pathway, with moderate connectivity.	
b.	Adjacent to an urban riverside plaza featuring a musical fountain, providing open spaces for leisure and gatherings, with good accessibility and frequent pedestrian activity.	
c.	A short central section located near the Riverside Park Music Square, offering scenic river views and green coverage, though with limited resting facilities.	
d.	Passing through a zone between residential neighborhoods and light industrial areas along the river, characterized by visible greenery but limited service and cultural facilities.	
e.	Mid-greenway segment extending toward a cultural landmark near Jiangyuelou, offering high vegetation coverage, shaded walkways, and strong accessibility, frequently used for recreational activities.	
f.	Located in a mixed-use zone near Tingjianglou, with adjacent community housing and small commercial clusters, providing shaded green corridors; however, it requires service facility enhancements.	
g.	A short section near institutional and commercial service areas, offering well-maintained walkways and easy accessibility, frequently used for commuting and exercise.	
h.	Extending along a residential corridor with pocket parks, providing visual openness and moderate greenery, but with limited public facilities.	

Table 1 (continued)

i.	A key greenway node near major residential communities and the Jiaoshan Scenic Area boarding platform, with high connectivity and rich vegetation, serves as a popular leisure and exercise area.	
j.	Transition section toward the eastern riverfront, passing near community housing clusters and providing moderate vegetation coverage with walkable connections.	
k.	The easternmost section of the greenway at the urban edge, characterized by low development levels, sparse vegetation, and lacking service facilities, is identified as a priority improvement zone.	

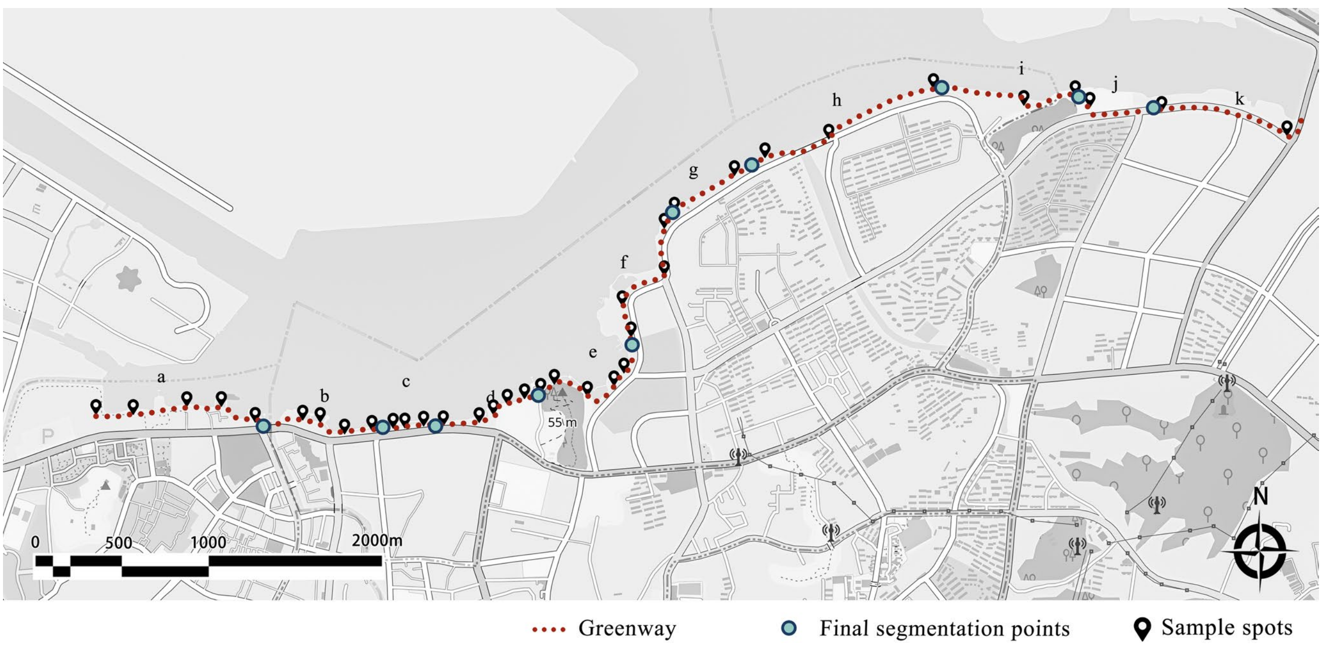

Fig. 5 Distribution of selected sample spots

were unsuitable for direct extraction. Therefore, 15 experts were invited from academia and professional practice, with backgrounds in architecture, urban planning, environmental design, and landscape architecture. All experts had substantial experience in landscape planning, design, or evaluation, ensuring the reliability and relevance of the weighting results (the questionnaire is presented in Table A2 in the appendix).

The evaluation was conducted hierarchically, with experts scoring the importance of the three main criteria, functional facilities (B1), visual landscape (B2), and cultural connotation (B3), followed by scoring the sub-criteria and individual indicators within each criterion. A nine-point scale was used, with higher scores indicating greater perceived importance.

Weight calculation using the entropy weight method

To determine the relative importance of each indicator, this study combined expert scoring with the entropy weight

Table 2 Detailed data of each greenway segment

Segment	Length (km)	Accessibility	Slow-mobility accessibility	Kernel density
a	1.05	10.00–10.80	32.50–34.50	122.50–154.00
b	0.70	8.75–9.40	29.50–31.50	35.00–68.00
c	0.30	7.80–8.30	28.00–30.00	84.50–120.00
d	0.65	8.10–8.65	26.50–28.50	130.00–155.00
e	0.80	8.75–9.40	29.50–31.50	34.50–50.00
f	0.90	9.15–10.00	32.50–33.00	0.00–34.00
g	0.55	11.00–11.50	35.50–37.50	0.00–34.00
h	1.20	11.00–12.00	38.50–40.50	35.00–68.00
i	0.85	12.50–13.00	41.50–43.50	52.00–84.00
j	0.45	13.00–14.00	44.50–46.50	69.00–100.00
k	0.75	14.00	46.50–49.00	0.00–34.00

Table 3 Landscape quality evaluation indicators system for the riverside greenway

Goal layer A	Criteria layer B	Sub-criteria layer C	Indicator layer D
Evaluation of the riverside greenway landscape in Zhenjiang City (A)	Functional facilities (B1)	Basic service facilities (C1)	Signage system completeness (D1)
			Service facility completeness (D2)
			Rest facility completeness (D3)
			Sanitation facility completeness (D4)
		Slow-mobility system (C2)	Transport accessibility (D5)
			Barrier-free path continuity (D6)
			Parking facility availability (D7)
			Walking and touring experience (D8)
	Visual landscape (B2)	Green landscape (C3)	Green view index (D9)
			Plant species diversity (D10)
			Rationality of plant arrangement (D11)
			Plant environment coordination (D12)
			Plant growth condition (D13)
		Pavement design (C4)	Surface texture (D14)
			Surface color (D15)
		Landscape elements (C5)	Diversity of landscape elements (D16)
			Aesthetic quality of elements (D17)
			Elements coordination (D18)
		Overall visual perception (C6)	Overall greenway maintenance level (D19)
			Safety for recreation and touring (D20)
			Cleanliness of green spaces (D21)
			Color diversity (D22)
	Cultural connotation (B3)	Local cultural development (C7)	Spatial cultural atmosphere (D23)
			Creation of traditional spatial axes (D24)
			Cultural symbolism integration (D25)
		Landscape gene expression (C8)	Inheritance of traditional cultural meaning (D26)
			Continuation of local cultural context (D27)
			Reflection of contemporary culture (D28)

method (EWM). The expert-based scoring results from Sect. "Selection of evaluation indicators" were directly incorporated into the EWM as the initial input for evaluating indicator importance. The EWM then objectively adjusted these preliminary values by incorporating the variability of the collected indicator data, thereby reducing subjectivity and enhancing methodological robustness.

Data standardization Indicator data were standardized using Z-score normalization:

$$Z_{ij} = \frac{(r_{ij} - \overline{r}_j)}{S_j} \tag{1}$$

where Z_{ij} was the standardized value, r_{ij} was the raw value, $\overline{r}_j$ was the mean, and S_j was the standard deviation for the j-th indicator.

Entropy calculation Entropy *Hj* for each indicator was calculated as:

$$H_j = -k \sum_{i=1}^{m} z_{ij} \cdot \ln z_{ij} \quad (2)$$

where *zij* was the proportion of the *i*-th sample under the *j*-th indicator, *m* was the number of samples, and $k=1/\ln(m)$. A higher entropy indicated greater uncertainty and less significance in the evaluation, while a lower entropy reflected higher information content and greater importance.

Weight calculation The final weight *Wj* for each indicator was computed as:

$$W_j = \frac{1-H_j}{\sum_{j=1}^{m}(1-H_j)} \quad (3)$$

where a higher weight denoted greater variability and importance of the indicator in the comprehensive evaluation.

Through this combined procedure, the final indicator weights reflected the expert-informed prioritization of landscape quality dimensions and the objective information of the collected dataset, providing a robust basis for the fuzzy comprehensive evaluation.

Fuzzy comprehensive evaluation

To evaluate the landscape quality of the riverside greenway, a fuzzy comprehensive evaluation (FCE) method was applied using the entropy-based weights calculated in Sect. "Weight calculation using the entropy weight method". A five-level evaluation scale (Very Poor, Poor, Fair, Good, and Excellent) and triangular membership functions were used to convert standardized indicator values into membership degrees, reflecting gradual differences in landscape quality.

A membership matrix was constructed using the 36 sample points across 11 segments, with each value representing the membership degree under each indicator. The entropy-derived weights were applied to this matrix to compute a weighted fuzzy evaluation, ensuring that the indicators contributed according to their calculated importance. The weighted average method was used to calculate the comprehensive landscape quality score for each sample, using:

$$S_i = \sum_{j=1}^{m} W_j \cdot x_{ij} \quad (4)$$

where S_i represented the comprehensive score of the ith evaluation object, xij was the membership degree of the iii-th object under the jth indicator, Wj was the weight of the jth indicator, and *m* was the total number of evaluation indicators.

The calculated comprehensive landscape quality scores were prepared for spatial visualization and analysis, supporting the identification of quality differences along the greenway for targeted improvement and management.

User perception survey and environmental data collection

A structured user perception survey was conducted among residents and visitors along the greenway to capture the experiential dimension. The survey employed a five-point Likert scale to assess perceptions about aesthetic quality, safety, comfort, accessibility, and overall satisfaction, aligning with the evaluation framework. The questionnaire consisted of three main sections: (1) respondents' basic information, (2) photographic documentation of each sample spot (including front, distant, left, right, and rear views), and (3) perceptual evaluation questions with corresponding options. To align with the spatial structure of the evaluation, the questionnaire was designed for each of the 36 sample spots based on on-site conditions, resulting in 36 tailored questionnaires.

These questionnaires were administered during holidays and weekends at each of the 36 spots to capture diverse user experiences. To expand the sample size, electronic versions of the questionnaires were uploaded to an online survey platform, enabling broader participation and scoring for each spot. The detailed structure and content of the user perception questionnaire are provided in Table A3 in the appendix.

After the initial on-site surveys, additional field distribution was conducted across different days and times during September to October 2024, supplemented by online questionnaires to broaden participation. By January 3, 2025, user perception data for all 36 spots were successfully collected, providing a robust dataset for subsequent analysis.

Results

Indicator weights and data distribution

To accurately determine the relative importance of the landscape quality indicators, this study employed an expert-based scoring approach. Therefore, 15 experts were invited to evaluate each indicator to ensure the reliability of the weighting results. Scores ranged from 1 to 9, with higher values indicating greater perceived importance. The aggregated expert scores indicated that visual landscape (B2)

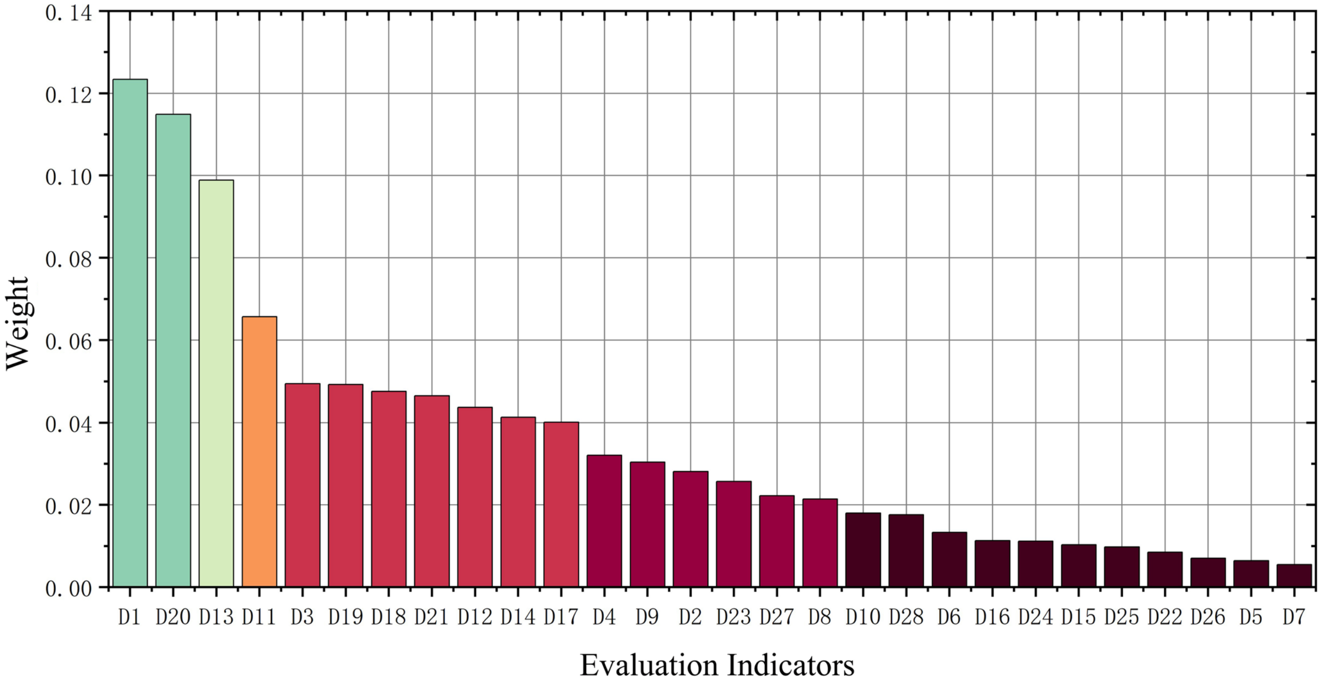

Fig. 6 Final weights of the landscape quality evaluation indicators for the riverside greenway

Table 4 Comprehensive score of landscape quality for each greenway segment

Segment	Mean value	Total value
A	3.72	18.60
B	4.81	14.42
C	4.79	19.15
D	3.68	18.41
E	4.82	19.29
F	4.51	18.02
G	4.97	9.95
H	4.17	12.51
I	5.23	15.69
J	4.89	9.78
K	2.21	2.21

received the highest importance (5.80), followed by functional facilities (B1) (4.07), and cultural connotation (B3) (3.87), highlighting the greater importance of visual and functional dimensions over cultural aspects in the greenway context. Following normalization and entropy weight calculation, the final weights of each indicator were obtained. The results were visualized in Fig. 6 to illustrate the distribution and relative significance across the indicators.

The top-ranked indicators included signage system completeness (0.12), safety for rest and touring (0.11), plant growth condition (0.10), plant arrangement rationality (0.07), and rest facility completeness (0.05). These indicated that accessibility, safety, vegetation quality, and facility completeness were critical for assessing the landscape quality of the riverside greenway. The complete ranked weights of all 28 indicators are presented in Fig. 6, providing a transparent basis for reproducibility and forming the foundation for the FCE, which integrated objective data and expert-informed priorities.

Fuzzy comprehensive evaluation results

The EWFCE was applied to assess the landscape quality of the Zhenjiang riverside greenway using 28 multi-dimensional indicators and the calculated indicator weights. This evaluation with user perception from both tourists and local residents, ensuring that both functional and experiential dimensions were reflected in the assessment.

The results demonstrated clear spatial differences in landscape quality across the greenway segments. As shown in Table 4, Segment I achieved the highest mean score (5.23), followed by Segments G (4.97), J (4.89), and E

(4.82). These segments are characterized by high vegetation coverage, well-developed facilities, and strong accessibility, contributing to a higher perceived quality and user satisfaction. In contrast, Segment K recorded the lowest mean score (2.21), reflecting limited development, insufficient vegetation, and inadequate supporting facilities, while Segments D and A scored lower, indicating areas requiring targeted improvement.

The evaluation results confirm that segments located near parks, community centers, and well-developed residential areas generally achieved higher scores, while segments with limited ecological infrastructure and incomplete facility development scored lower. These findings align with user perception survey results, indicating consistency between objective evaluations and subjective user experiences regarding landscape aesthetics, safety, and comfort. Overall, the results provide a quantitative foundation for identifying priority areas for targeted landscape quality improvements and for informing effective management and planning of urban riverside greenways.

Landscape quality evaluation across sample spots

Using the EWFCE, landscape quality scores were calculated for each of the 36 points, capturing variations in functional facilities, visual landscape quality, and cultural connotation across the greenway corridor. As shown in Fig. 7, the overall scores across the samples ranged from 2.22 (K1) to 6.14 (E3), indicating significant variation in landscape quality along the evaluated greenway.

Higher scores were observed at E3 (6.14), E2 (5.44), B3 (5.37), I2 (5.95), and C4 (5.04), which were near well-developed park areas, community nodes, and segments with high vegetation coverage, visual diversity, and facility completeness. These areas provided enhanced ecological and recreational functions, contributing to greater user satisfaction and perceived landscape quality. In contrast, lower scores were recorded at K1 (2.22), D4 (2.37), A4 (2.53), A5 (2.61), and D3 (2.75), reflecting areas with incomplete development, limited vegetation, lower accessibility, and insufficient supporting facilities. These locations often corresponded to transitional or underdeveloped sections, indicating the need for targeted interventions to improve safety, comfort, and ecological connectivity.

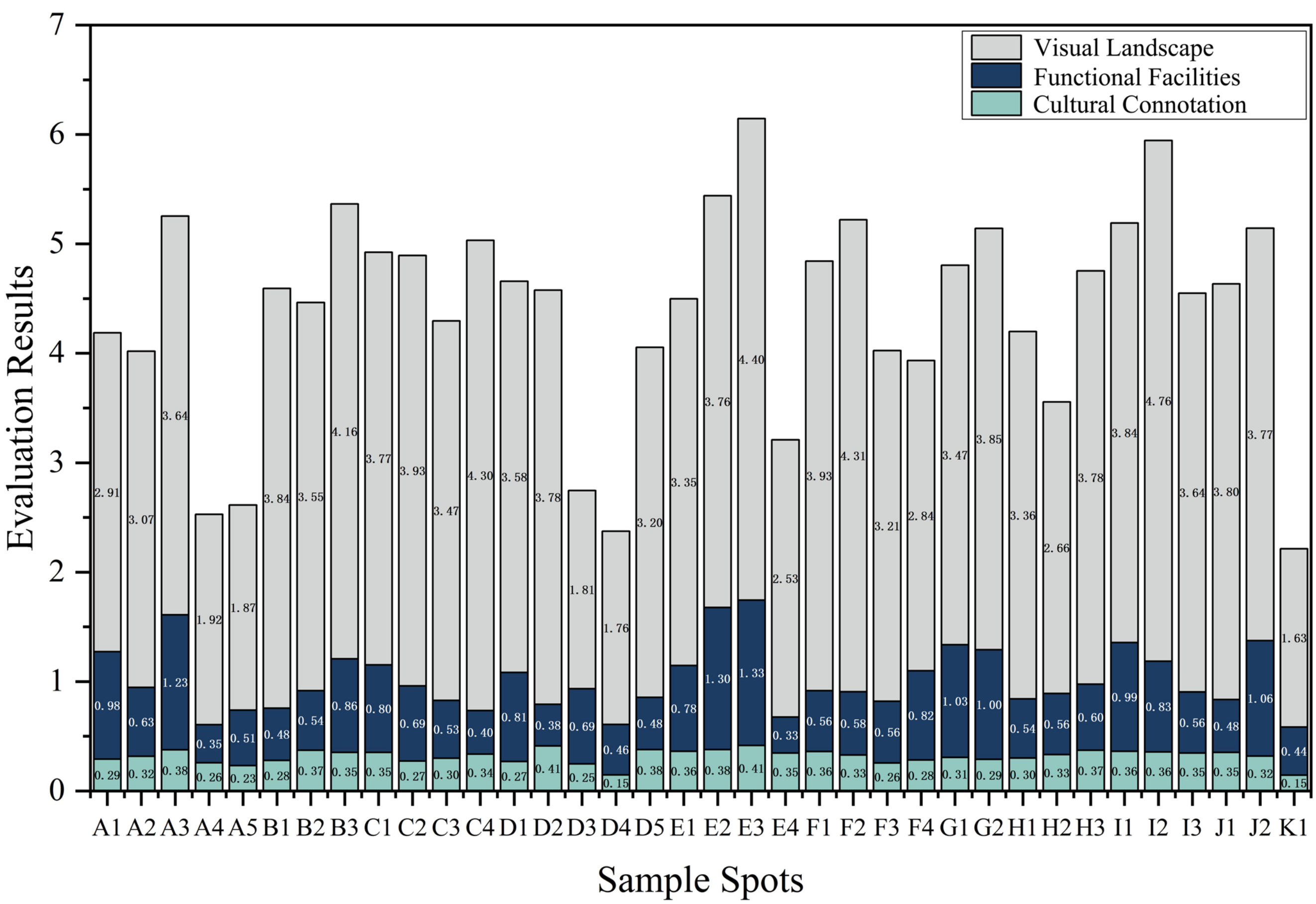

Fig. 7 Landscape quality evaluation results for each sample spot

This sample-based analysis offered a fine-grained perspective on landscape quality distribution that complemented the segment-level evaluation results. The variability among samples highlighted localized strengths and deficiencies, providing actionable references for targeted landscape enhancement and prioritization. Moreover, the alignment between higher objective scores at specific sample points and positive user feedback from the survey further validated the robustness of the evaluation framework.

Indicator-level performance across evaluation dimensions

To further analyze the detailed landscape quality characteristics, the study extracted the average performance scores of all sampled spots under each evaluation indicator across three primary dimensions: functional facilities, visual landscape, and cultural connotation. This enabled a clear understanding of the relative strengths and weaknesses within each dimension, providing targeted insights for future landscape enhancement (Fig. 8).

Regarding functional facilities, indicators D1–D8 showed an overall average score of 2.63, indicating a moderate facility provision along the greenway. Furthermore, D2 (service facility completeness) and D7 (parking facility availability) received the lowest average scores, at 1.92 and 2.33, respectively, revealing significant deficiencies. In contrast, D5 (transport accessibility) and D6 (barrier-free path continuity) performed relatively well, with average scores of 3.25 and 2.77, respectively, reflecting a relatively strong performance in transportation connectivity and accessibility infrastructure.

Regarding visual landscape, D9–D22 had an overall average score of 3.39, reflecting a moderately high visual quality in the spatial design. Particularly, D16 (diversity of landscape elements) and D17 (aesthetic quality of landscape elements) had lower average scores of 2.96 and 2.83, respectively, suggesting deficiencies in the quantity and aesthetic quality of landscape installations. Conversely, D12 (plants environment coordination) and D22 (color diversity) achieved higher scores of 3.44 and 3.38, respectively, indicating significant plant-environment coordination and spatial color diversity.

Regarding cultural connotation, D23–D28 had an overall average score of 3.17, suggesting that the greenway achieved a commendable level of cultural integration and

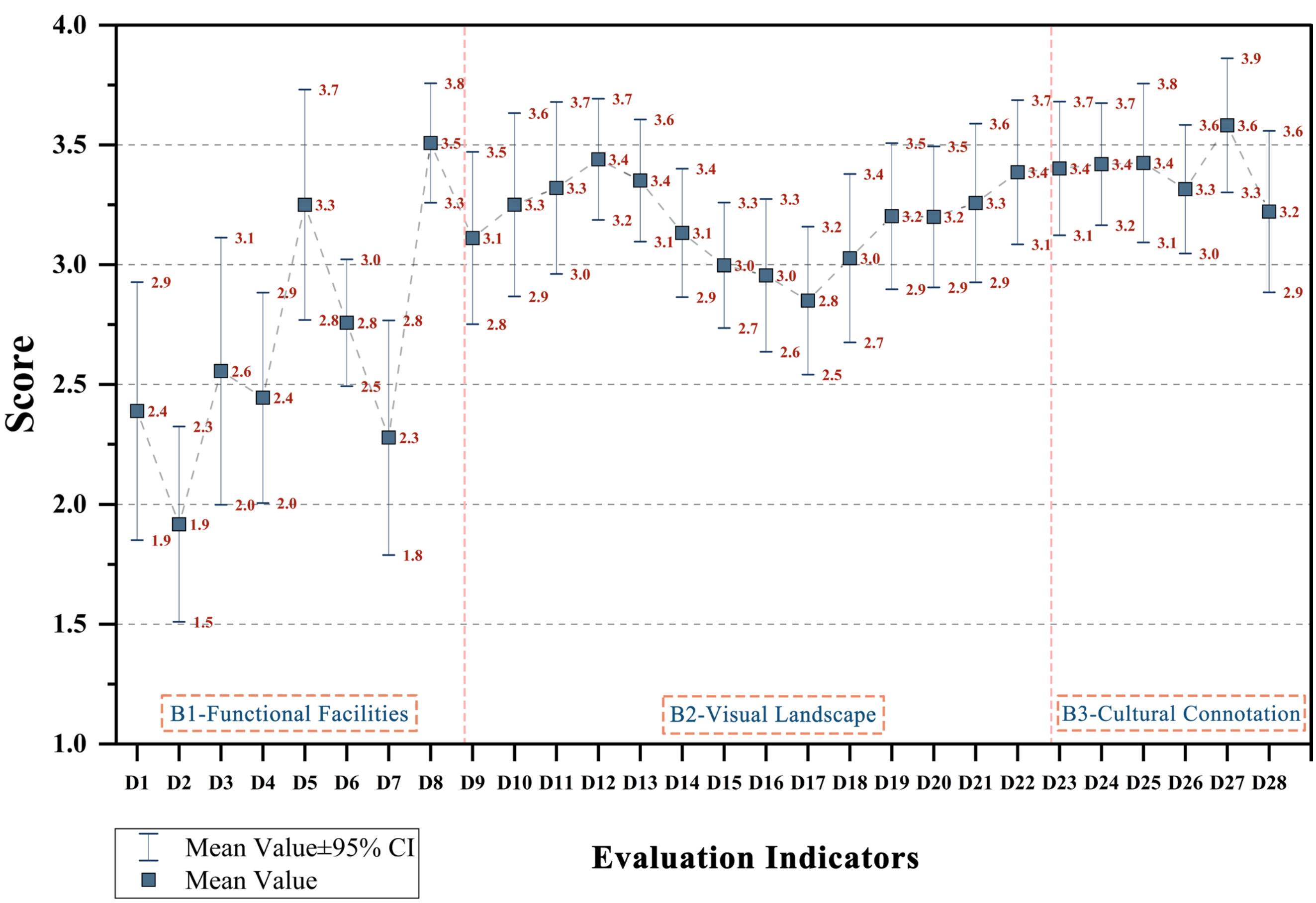

Fig. 8 Mean score of evaluation indicators across three dimensions

expression. Significantly, D28 (reflection of contemporary culture) had a relatively lower score of 3.22, reflecting room for improvement. However, D27 (continuation of local cultural context) performed notably well, with a score of 3.58, indicating the preservation and reflection of local historical and regional cultural features within the design.

User perception-based assessment

To accurately assess the performance of each sample spot from resident and tourist perspectives, the study disaggregated the overall survey data to analyze perceptual differences. A total of 1,117 valid questionnaires were collected, with approximately 35.48% from tourists and 64.52% from residents, ensuring robust and representative data. The analysis presented tourist scores, resident scores, and their differences (calculated as tourist scores minus resident scores) across all evaluation factors for each sample spot (Fig. 9).

The heatmap revealed notable differences between resident and tourist perceptions across multiple evaluation factors. For instance, K1 exhibited a high positive difference in D6 (+1.28), indicating that tourists rated accessibility higher than residents, likely reflecting differences in expectations or usage patterns. Similarly, E1 showed a pronounced positive difference in D23 (+1.62), indicating stronger perceived cultural appeal among visitors. Enhancing localized cultural features may help foster a deeper connection for residents as well.

Conversely, several sample spots displayed significant negative differences. For example, sample spot D2 recorded a difference of -1.98 in D15, indicating that residents perceived pavement color more positively than tourists, possibly due to their greater familiarity with the local environment. Additionally, C4 showed a -1.03 difference in D26, suggesting that residents were more attuned to cultural continuity and the local context than tourists. Overall, factors with differences exceeding ± 1.0 indicated perception gaps that merit further exploration. These discrepancies highlighted the importance of incorporating visitor and resident perspectives in landscape quality evaluations to ensure balanced, inclusive, and user-centered greenway design improvements.

This study compiled the scores of each sample spot under qualitative factors from resident and tourist perspectives (Fig. 10). The results indicated that minor differences between scores from tourists and residents were observed in sample spots A3 (−0.13), A4 (−0.09), B1 (−0.21), B3 (0.06), C1 (0.04), J1 (−0.05), J2 (0.01), and K1 (0.05).

Except K1, the other sample spots had relatively high scores from both perspectives, indicating that spots units provided a good landscape experience to residents and tourists. However, K1 had not been fully developed; therefore, it had a bad performance from both perspectives. Meanwhile, A2 (1.02), D2 (−1.11), and E1 (0.99) showed relatively significant differences in the dual evaluation. Specifically, A2 and E1 were highly evaluated by the tourists, yet were normally evaluated by the residents. It was assumed that both spots were adjacent to two scenic spots (Jinshan Temple and Beigu Mountain), and tourists were attracted by the unique landscape, leading to a relatively high evaluation, while residents had become accustomed to them.

However, D2 got a high evaluation from the locals, yet a mediocre score from tourists, likely because D2 had a relatively low accessibility (8.10–8.65), a certain distance from each scenic spot, and landscape homogeneity. Concerning the different needs of residents and tourists for greenways, a high green view index (38.72%) of D2 provided a good landscape experience for residents to rest and walk; however, it did not receive a high evaluation from tourists with limited parade time.

Comparative analysis of greenway segments and sample spots

Figure 11 illustrates the multi-criteria evaluation scores for each segment under all assessment indicators, enabling the identification of segments with strong or weak landscape performance across the greenway. Segment I demonstrated the highest scores, particularly for visual landscape, reflecting superior performance in design, environmental ambiance, and aesthetics. Segments E and J excelled in functional facilities, including service availability, transportation connections, and accessibility. Segment F achieved high scores for visual landscape, with plant configuration and color coordination as its strengths. In contrast, Segment K exhibited the lowest scores across all dimensions due to incomplete development and insufficient facilities.

To further examine localized differences, Fig. 12 compared five high-performing (A3, B2, E2, E3, I2) and five low-performing (A4, A5, D3, D4, K1) sample spots. High-performing spots displayed diverse strengths: A3 excelled in aesthetic appeal, B2 featured well-planned amenities, E2 and E3 performed consistently well across all dimensions, with E3 being particularly strong in cultural integration, and I2 achieved the highest comprehensive score due to its landscape-plant coordination and functional infrastructure. In contrast, low-performing spots suffered from underdeveloped infrastructure, inadequate cultural representation, and poor spatial coherence, with A4 and K1 lacking even basic facilities.

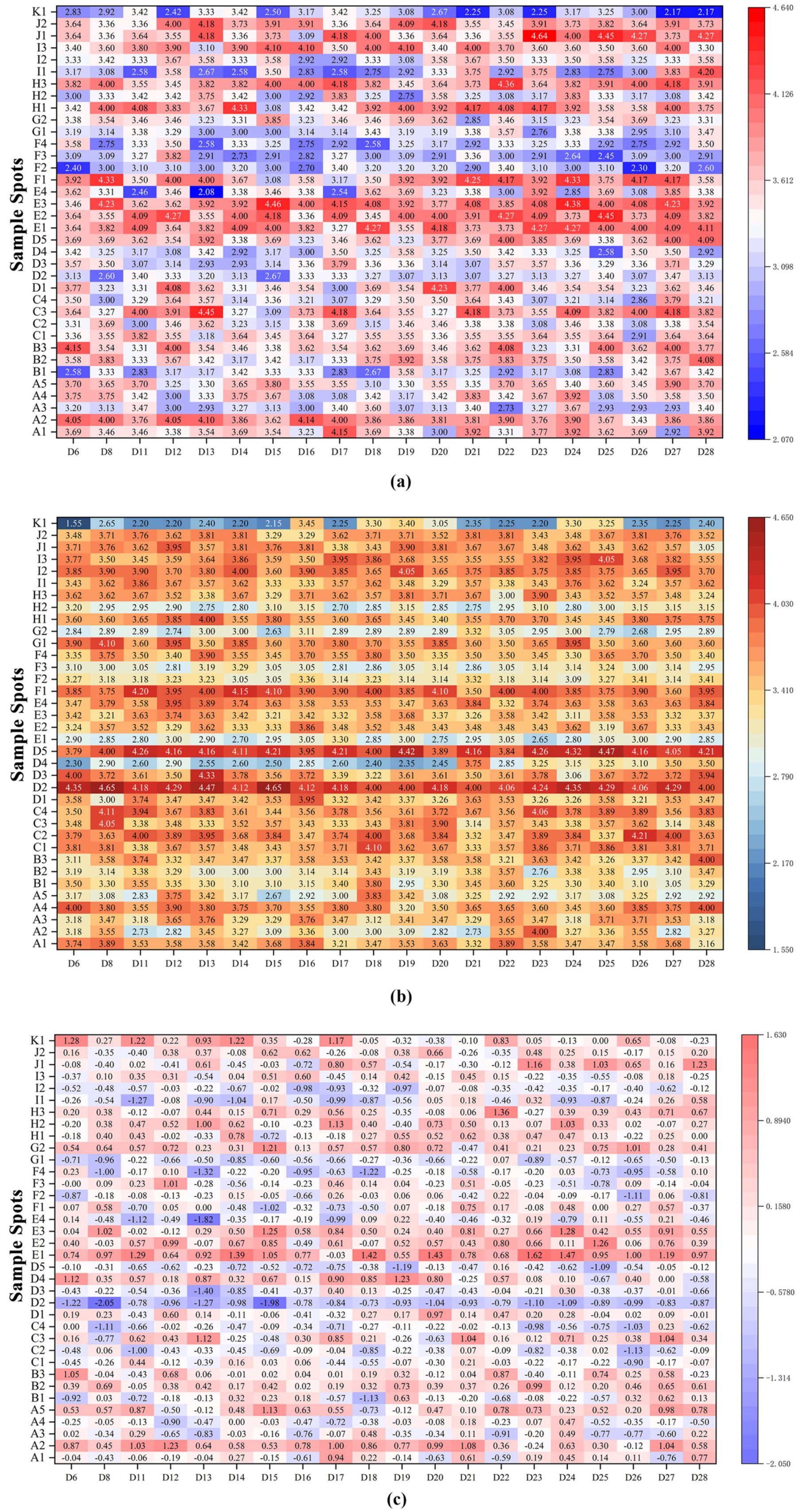

Fig. 9 Resident and tourist perception scores and differences value. **a** Tourist evaluation results, **b** Resident evaluation results, **c** Differences between the two groups

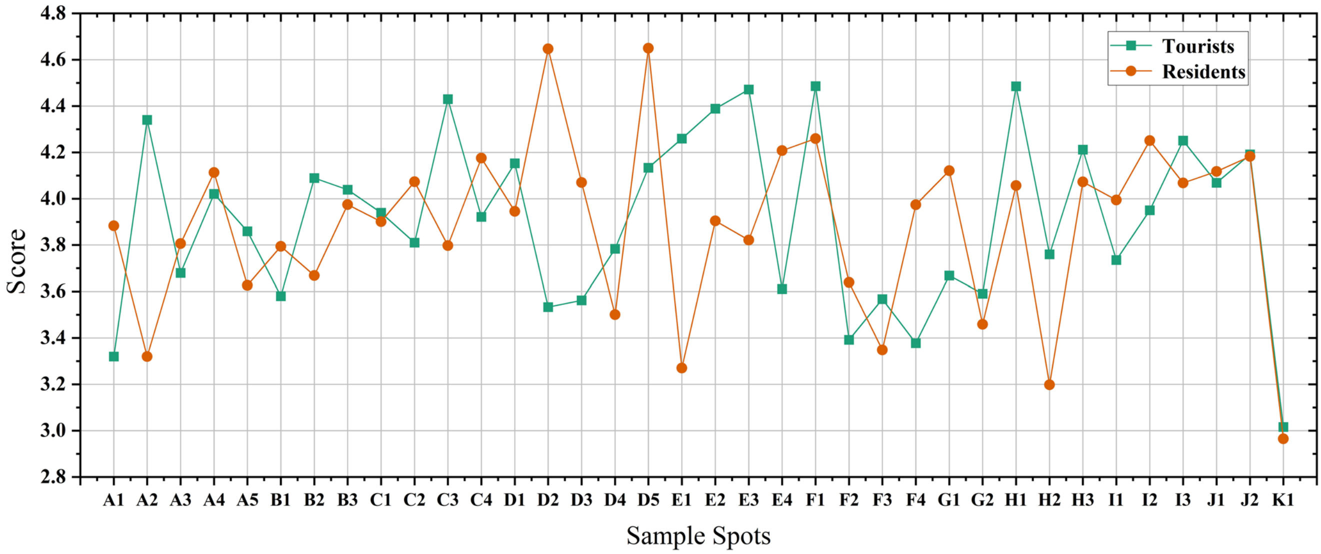

Fig. 10 The scores of each sample spot from perspectives of residents and tourists

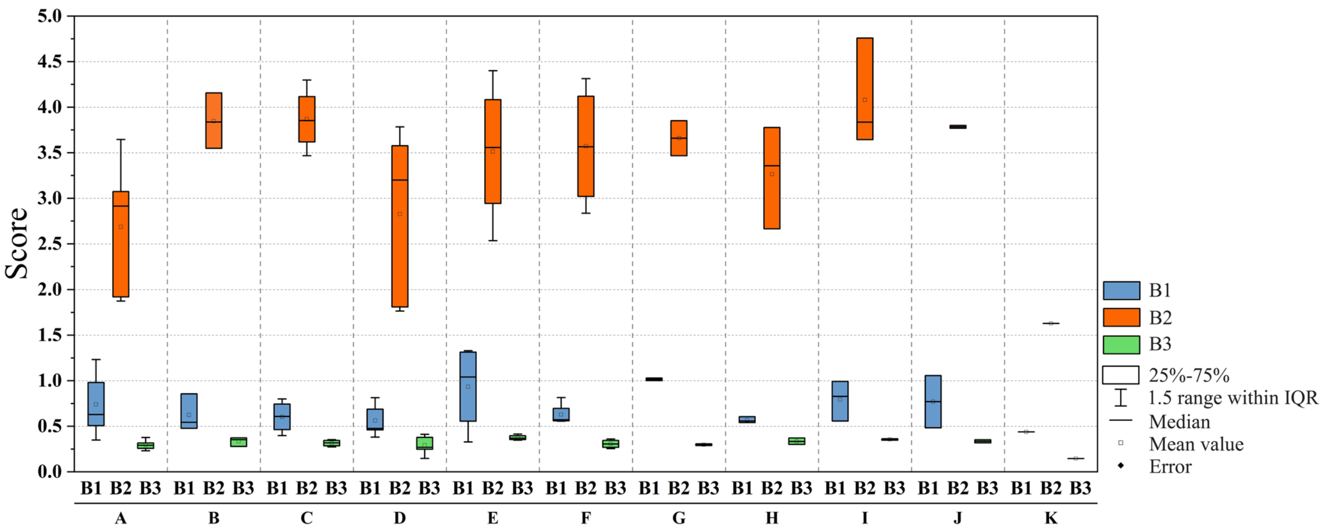

Fig. 11 Multi-criteria landscape quality scores across greenway segments

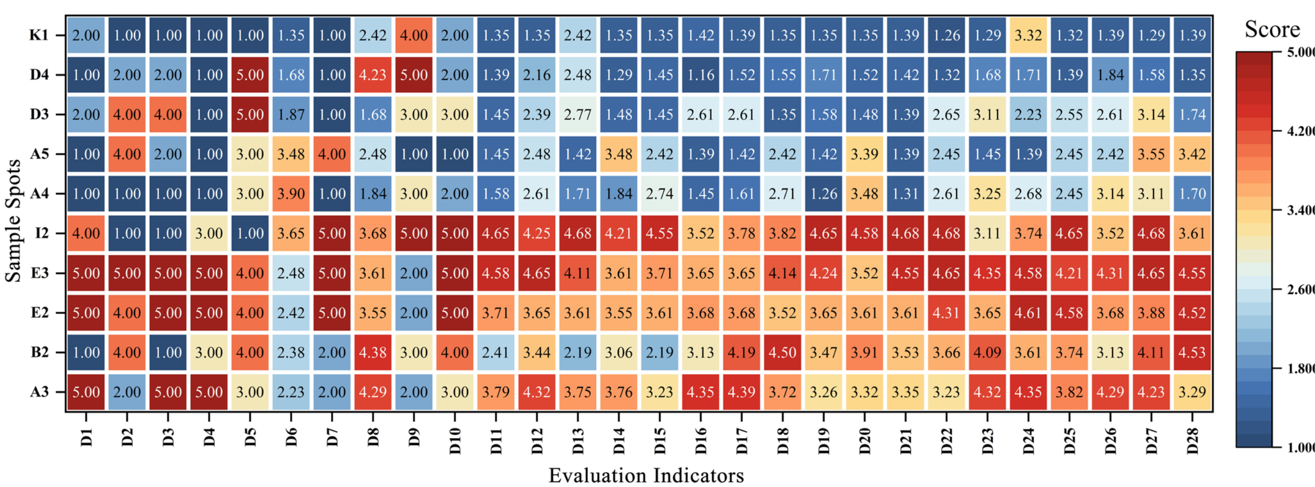

Fig. 12 Landscape quality evaluation of selected sample spots

Discussion

Interpretation of landscape quality patterns and user perceptions

The evaluation results revealed spatial heterogeneity in the landscape quality of the Zhenjiang riverside greenway, reflecting differences in functional facilities, accessibility, visual landscape, and cultural connotation across greenway segments and sample spots. Segments I, G, J, and E consistently demonstrated high comprehensive scores, characterized by well-developed facilities, high vegetation coverage, and strong accessibility. Segment I benefited from continuous canopy cover and open river views, while Segment E featured activity plazas and clear signage, facilitating wayfinding and user rest. Segments G and J provided shaded resting areas with nearby cultural elements, enhancing comfort and experiential quality for residents and visitors. These results align with Nordh et al. (2011) who demonstrated that vegetation richness and the presence of green structural elements, such as grass and trees, significantly enhanced users' perceived restorative quality and preference in urban green spaces.

In contrast, Segment K and sample spot K1 and D4 exhibited lower scores, indicating ecological and functional deficiencies, similar to Korea's urban stream restoration cases documented by Bae (2011), where infrastructural incompleteness and limited recreational facilities in partially restored canalized streams led to reduced user satisfaction and perceived amenity value. Specifically, Segment K, located at the greenway's eastern endpoint, lacked sufficient shading and seating, while D4 featured narrow, exposed paths with sparse vegetation, which reduced comfort and visual interest.

The indicator-level analysis revealed that while visual landscape achieved a moderately high average score (3.39), functional facilities (2.63) and cultural connotation (3.17) lagged, especially in service facility completeness and cultural continuity. This is consistent with Li et al. (2024) who found that in rapidly urbanizing areas, greenway planning often prioritized visual enhancements, such as vegetation arrangement and scenic views, over functional and cultural improvements, potentially constraining user inclusivity. User perception analysis indicated that residents and tourists exhibited differing evaluations across segments and factors. For instance, tourists rated accessibility (D6) and visual elements (D18) higher in specific spots, while residents valued vegetation quality (D13) and cultural continuity (D23).

Furthermore, segments near activity plazas (B and C) attracted tourists for their visual appeal and ease of access, while segments F and H were valued by residents for their quieter green spaces and the presence of cultural signage, illustrating how local identity and daily familiarity shaped user preferences. These differences aligned with Bertram and Rehdanz (2015b, a)., who, in their cross-city study of urban park use and perception in Europe, observed that park users prioritized different attributes, with tourists focusing on immediate visual and accessibility experiences, while residents valued deeper cultural and ecological aspects shaped by regular use.

The alignment between objective fuzzy evaluation scores and positive user perceptions in high-performing segments validated the robustness of the integrated evaluation framework. However, the perception gaps in certain indicators highlighted the importance of incorporating feedback from diverse user groups into greenway planning to support inclusive and context-sensitive designs (Akpinar 2016). Overall, these findings emphasized that ecological and visual improvements were critical for enhancing landscape quality. However, functional facilities and cultural integration required focused interventions to ensure that urban greenways were aesthetically pleasing, socially inclusive, and ecologically functional.

Implications for urban greenway planning and design

The findings offer several practical insights for the planning and design of urban riverside greenways to enhance landscape quality, user satisfaction, and ecological functionality. The association between vegetation quality, canopy cover, and higher evaluation scores highlighted the need to prioritize greening strategies in underperforming segments. Incorporating diverse plant species and ensuring seasonal visual interest could improve ecological resilience and user experience, aligning with evidence that vegetation diversity contributed to urban thermal comfort and aesthetic value (Zheng et al. 2024b).

The variability in functional facility scores suggested the necessity to improve infrastructure, particularly in segments with low accessibility and incomplete rest and service facilities. Providing barrier-free pathways, adequate seating, signage systems, and well-maintained sanitary facilities could increase greenway usability, particularly for older residents and users with mobility limitations (Audate et al. 2024). The observed differences between tourist and resident perceptions underscored the importance of integrating cultural elements and local identity into greenway design. While tourists emphasized visual elements and accessibility, residents valued vegetation quality and cultural continuity. Therefore, enhancing cultural signage, public art installations, and interpretive trails could foster a sense of place while catering to the expectations of diverse user groups, ensuring that greenways meet visitor attractiveness and the daily experiential needs of locals (Carmona 2021).

Additionally, the study demonstrated the value of multi-criteria evaluation frameworks that integrate objective spatial data with user perceptions in supporting evidence-based, user-centered greenway planning. Planners can utilize spatial and ecological evaluation results to identify critical improvement areas, while user perception data can guide refinements aligning with community preferences, promoting inclusive and context-sensitive interventions (Kabisch et al. 2016). Urban riverside greenways should be positioned as key green infrastructure components within broader urban climate adaptation strategies, providing microclimate regulation, stormwater management, and accessible recreational spaces that promote public health (Wolch et al. 2014). Integrating landscape quality evaluation into routine greenway monitoring can help cities iteratively improve green space design and management to meet the evolving needs of residents while addressing environmental challenges. By addressing the identified gaps and by leveraging integrated evaluation methods, urban planners can enhance the functionality, inclusivity, and ecological value of riverside greenways, ensuring effective contribution to sustainable and livable cities.

Limitations and future research

While this study provides comprehensive insights, several limitations should be acknowledged. Its geographical scope is limited to a single case in Zhenjiang, which may restrict the generalizability of the findings to greenways in cities with different climatic, socio-cultural, and urban forms (Jay and Schraml 2009; Kabisch and Haase 2014; Lin et al. 2015). Future studies should validate the proposed EWFCE framework across diverse urban settings to examine its adaptability and scalability.

The indicator system, although covering ecological, spatial, and cultural dimensions, does not incorporate parameters such as thermal comfort, air quality, nocturnal safety perceptions, or biodiversity assessments, which are increasingly relevant in greenway planning for climate adaptation and public health (Kabisch and Haase 2014; Demuzere et al. 2014; Li et al. 2023). Integrating microclimate modeling (e.g., using ENVI-met) and biodiversity indicators in the evaluation framework can enrich assessments and provide holistic insights for greenway design under climate variability.

The study has temporal limitations, as the evaluation and user perception surveys were conducted within specific seasons. Seasonal changes and extreme weather events can significantly affect vegetation, thermal comfort, and visitation patterns (Norton et al. 2015). Longitudinal studies incorporating year-round data would provide a better understanding of the seasonal dynamics influencing landscape quality and user satisfaction. While the study incorporated user perception data, it primarily relied on structured surveys. Exploring real-time user feedback through social media data, mobile sensing, and participatory mapping can capture dynamic perceptions and behavioral patterns, providing a richer analysis (Cheng et al. 2023).

Future research should explore the integration of health impact assessments with landscape quality evaluations, considering how greenway design influences physical activity, mental well-being, and social cohesion. Additionally, they should assess how greenways function as a part of broader green networks in enhancing urban resilience and ecosystem services. Hence, future research can strengthen the applicability and comprehensiveness of landscape quality evaluations, supporting greenway planning that is ecologically functional, socially inclusive, and adaptable to evolving urban challenges.

Conclusion

This study developed and applied a combined EWFCE and user perception framework to comprehensively assess the landscape quality of the Zhenjiang riverside greenway. Based on the results, the following key conclusions were drawn. Vegetation quality, accessibility, and well-maintained facilities are critical determinants of high landscape quality in urban riverside greenways. Segments with higher canopy coverage, barrier-free pathways, and clear signage achieved higher evaluation scores, underscoring the importance of ecological and infrastructural elements in enhancing user satisfaction.

Visual landscape quality is a relative strength, while deficiencies were identified in functional facilities and cultural integration. Although the aesthetic aspects were generally well-received, gaps in rest facilities, service infrastructure, and cultural expression indicated areas for improvement in greenway planning and design. Residents and tourists exhibited differing perceptions of landscape quality, highlighting the need to integrate multi-group user perspectives into greenway evaluation. While tourists prioritized accessibility and visual appeal, residents valued vegetation quality and cultural continuity, emphasizing the importance of inclusive and user-centered approaches in greenway development.

Overall, this study demonstrated the effectiveness of combining EWFCE with user perception analysis to identify spatial heterogeneity, strengths, and deficiencies within urban riverside greenways. The proposed framework offers a practical, systematic, and transferable tool to support evidence-based greenway planning and optimization, contributing to the development of ecologically resilient, socially inclusive, and user need-aligned urban green infrastructure.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11355-025-00694-1.

Acknowledgements The author would like to thank Dongmei Li for assisting in conducting on-site investigations and questionnaire surveys. We also thank the anonymous reviewer for their constructive comments and suggestions.

Author contributions Conceptualization: Yingnan Li, Zhicheng Zhou, Lu Ding; Methodology: Yuedong Wang, Yuhan Zhang, Zipeng Song, Lu Ding; Formal analysis and investigation: Yingnan Li, Zhicheng Zhou, Yakun Chang, Lu Ding; Data curation: Menglin Zhou, Yuhan Zhang, Zipeng Song; Writing—original draft preparation: Yingnan Li, Lu Ding; Writing—review and editing: Zhicheng Zhou, Yuedong Wang, Lu Ding; Visualization: Yakun Chang, Menglin Zhou, Lu Ding; Funding acquisition: Yingnan Li, Lu Ding; Resources: Guangxi Shen, Lu Ding; Supervision: Lu Ding.

Funding This study was supported by the National Natural Science Foundation of China (No. 42571103), the Jiangsu University Senior Talent Fund (No. 19JDG004), the Talent Project of the "Double-Entrepreneurial Plan" in Jiangsu Province, and the National Research Foundation of Korea (No. NR060142).

Data availability Data supporting the findings are available within the article and its supplementary material. Raw data are available from the corresponding author upon reasonable request.

Declarations

Conflict of interest The authors declare no conflicts of interest.

Ethical approval and consent to participate All ethical aspects of the research, such as confidentiality, protecting the environmental and human health of participants, not forcing them to participate, and the freedom to withdraw from participation, have been observed.

Consent for publication The authors express their full consent for the publication of this article in this publication.

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