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RESEARCH ARTICLE

Micro-resilience assessment tool for living streets: Development, testing, and application in Chinese Jiangnan's small and medium-sized cities

Chen Liu [a], Haoran Ma [b], Ren Zhou [a], Zhaolian Xing [a], Weimin Guo [a,*]

[a] School of Design, Jiangnan University, Wuxi 214122, China
[b] Institute of Space and Earth Information Science, The Chinese University of Hong Kong, Hong Kong SAR, China

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Abstract Improving micro-resilience in living streets enhances the daily quality of life for residents and contributes to the city's overall resilience. However, current research on urban resilience primarily focuses on macro-scale and large cities, neglecting the unique resilience needs of small and medium-sized cities, especially in close-to-daily life scenarios. This study assessed the specific manifestations of resilience deficiencies in typical living streets within the Chinese Jiangnan region's small and medium-sized cities and conducted an in-depth review of relevant literature across related dimensions, extracting and drafting a theoretical living streets resilience framework. A resilience assessment tool, ESO (Environment-Social-Operation), was developed based on this framework and refined through two Delphi surveys with experts and practitioners. The final actionable assessment framework included eight secondary and 37 tertiary indicators. A pilot test of the tool was conducted on 16 streets in 4 cities, yielding an intraclass correlation coefficient (ICC) of 0.81 (95% CI = 0.69–0.90), demonstrating the tool's robustness and feasibility. This tool considers built-environment factors and social-function elements. It provides a systematic tool for enhancing resilience in living streets in small and medium-sized cities, offering guidance and decision-making support for urban renewal and management practices that enhance resilience at both micro and indirectly promoted macro levels.

* Corresponding author.
E-mail address: gwm6316@126.com (W. Guo).
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1. Introduction

Living streets, which are located next to residential areas and life service facilities (Aman et al., 2019), serve as essential urban spaces supporting public life (Bain et al., 2012). As the "last mile" of urban resilience transmission, living streets connect complex urban systems upwards while providing spaces for daily life downwards (Kriznik, 2018). Micro-resilience refers not only to the ability of physical spaces to return to standard functionality after a disaster (Ribeiro and Goncalves, 2019), but also to the comprehensive stability of spaces and their associated entities under social, cultural, economic, and informational coordination during minor changes or disruptions (Chelleri et al., 2015). This exploration of micro-level urban resilience, especially through the renewal of urban spaces, is increasingly recognized by various planning and policy frameworks (Dastjerdi et al., 2021; Samuelsson et al., 2019) and contributes to achieving sustainable development goals (SDGs), such as promoting health and well-being (SDG 3) and fostering sustainable cities and communities (SDG 11).

From a policy perspective, resilience has gradually integrated into countries' construction goals and planning frameworks worldwide (Meerow et al., 2016). This is due to the increasing prevalence of unforeseen crises, such as public health emergencies, climate extremes, and socio-economic disruptions, with cities being regarded as key hubs for addressing these challenges (Zhu et al., 2020). The normalization of change has shifted research toward focusing more on urban resilience in multiple dimensions (Hawken et al., 2021; Rodriguez-Izquierdo et al., 2022). Resilience here encompasses not only short-term recovery but also long-term adaptability, the ability to maintain vitality and even improve under persistent stressors (Madrid-Solorza et al., 2024), preparing for potential shocks (Amirzadeh et al., 2022).

However, much of the research has concentrated on large-scale urban systems and macro-level solutions (Andrić and Lu, 2017; Datola et al., 2022; Zhai et al., 2015), such as examining the recovery capabilities of large infrastructures, cities and regions, prioritizing investigations into resilience against large-scale natural disasters (Andersson et al., 2021; Berkes et al., 2008), often overlooking the micro-resilience directly affecting daily life (Kourtit et al., 2022). This imbalance may hinder practical urban renewal efforts, as it ignores the potential of bottom-up actions to drive overall urban resilience (Jin and Shao, 2024) and raises concerns about the effectiveness of resilience strategies (Bergström and Dekker, 2014). Fortunately, in recent years, many countries have recognized the importance of this issue, with their development agendas increasingly emphasizing the synergistic effects of urban resilience at multiple levels, particularly at the micro-scale (Longbin and Hanping, 2024; Rogov and Rozenblat, 2018).

Nevertheless, small and medium-sized cities have received less attention than large cities (Jia et al., 2022), and micro-level issues are more complex, necessitating more relevant, context-specific goals (Liu et al., 2018). Although these cities are relatively small in scale, they have to bear comprehensive functions, and the available resources are limited (Greene et al., 2017; Longbin and Hanping, 2024). Cities in the Jiangnan region of China as an example, have good development foundation, and possess great potential for promoting regional development. Living streets in these cities still serve a large population and bear rich natural and cultural heritages, but now struggle to adapt to changes and lack resilience focus. Their shared spatial features and resilience challenges make them ideal for systemic study (Liu and Liu, 2023). Nowadays, many urban renewal initiatives focus on these streets, making the development of standards and guidelines for enhancing resilience directly impact personal well-being and urban environments. The uniqueness, diversity, and transitional scale of living streets make them an ideal focus for micro-resilience research (Konecka-Szydłowska, 2018).

To address these challenges, developing an assessment tool tailored to the resilience of living streets in small and medium-sized cities in the regional context is crucial. Past studies have developed many tools for assessing resilience, which are used to measure different types of urban spaces. Mondal et al. (2023) Developed Micro-resilience Index for Indian Sundarban. Sharifi (2016) analyzed thirty-six selected community resilience assessment tools. Xu et al. (2020) have established a three-level practical indicator system for complex urban public spaces such as railway stations and airport terminals. The study of resilience has become increasingly refined, with many focusing on the dynamics of spatial usage at the micro-level (Erkip et al., 2014; Naghibi, 2024) and its importance in promoting residents' well-being and urban resilience (Dastjerdi et al., 2021; Naghibi et al., 2025; Samuelsson et al., 2019). Sharifi (2019) prioritizes the physical form of urban streets contributing to resilience but over the nuanced interplay of micro-level street activities, placemaking actions, cultural narratives, and flexible operations that shape public living space and residents' resilience. While some studies provide theoretical frameworks for resilience in small and medium-sized cities in the Jiangnan region (Liu and Liu, 2023; Xiong et al., 2022), a systematic resilience assessment tool and pathways for improvement are still lacking.

To bridge these gaps, this study develops and validates the ESO (Environmental-Social-Operational) resilience assessment tool, tailored to the unique characteristics of living streets in small and medium-sized cities in Jiangnan and evaluates its usability through pilot testing. The ESO tool focuses on the micro-scale aspects of resilience and explores pathways for promoting macro-level resilience through small-scale urban renewal actions. The study aims to answer key questions about the dimensions of resilience in such streets: 1) What aspects of resilience should be assessed? 2) How should resilience be evaluated? and 3) How can resilience be enhanced? Addressing these questions is crucial for assisting government agencies, urban planners, and stakeholders in improving the resilience of streets to withstand future shocks.

2. Background

This section delves into the fundamental concepts of living streets and micro-resilience, exploring their definitions, characteristics, and significance in urban planning and design. Furthermore, we will elaborate on the reasons for

choosing Yixing City as the case study area and provide an overview of its living streets.

2.1. The spatial scope of living streets

Living streets related to residents' daily lives, providing essential public functions and facilitating social interaction (Bain et al., 2012). Due to their significant role in urban life, urban planners worldwide have emphasized the design of living streets (Biddulph, 2012). The concept of the woonerf, introduced in the Netherlands, is similar to that of living streets, referring to spaces primarily designed for residential functions, emphasizing low-speed driving, shared spaces, and a social atmosphere (Ben-Joseph, 1995). In the United States, the U.S. Environmental Protection Agency released the Denver Living Street guidelines in 2014, emphasizing transforming streets into living spaces that promote active lifestyles adapted to urban development (Moulton and FAIA, 1999).

This study builds on the Shanghai Street Design Guidelines (2016), China's first comprehensive street design guidelines defining and categorizing street types (Istrate et al., 2021). Living streets are defined here as those streets along which the facilities are mainly community, life-service-oriented businesses, small and medium-scale commercial facilities, and public service facilities serving residents (Fig. 1). These streets typically pass through residential communities and serve as key locations for public life, play a critical role in providing environmental, social, and cultural functions (Liu and Liu, 2023). In recent years, many small and medium-sized cities have undertaken various living street renovation projects, but these efforts often focus only on superficial material upgrades. Few practices consider how these renovations can align with broader urban resilience goals (Coyle, 2011). What are the intrinsic problems faced by living streets? How can the level of resilience of these streets be evaluated? How can micro-level actions enhance resilience at the micro to macro scales in these cities? Developing an assessment tool could potentially address these issues.

2.2. The scope of micro-resilience

Resilience is a systemic attribute that can be consciously cultivated through appropriate practices and policies (Andersson et al., 2021). Micro-resilience emphasizes individuals, communities, and specific spaces' multifunctionality, adaptability, stability, and recovery ability when faced with localized pressures and shocks (Cutter et al., 2014; De Carli, 2016). In recent years, there has been an increasing focus on the resilience of urban spatial environments at more minor, more localized scales (Desouza and Flanery, 2013; Naghibi, 2024). Scholars have recognized that micro-resilience is crucial for the continued adaptation of individuals, communities, cities, and regions (Champlin et al., 2023). This perspective, shifting from macro to micro resilience, focuses more on the specific responses of physical spaces and the people they support, particularly those aspects that can be improved through bottom-up micro-actions. As mentioned above, many frameworks have been developed in resilience studies. Sharifi (2019) proposed a street comprehensive resilience analysis framework, which can provide directions for exploring issues related to street resilience. Based on this framework, we preliminarily defined the scope of research on the resilience of living streets (Fig. 2).

2.3. Study area

Living streets in small and medium-sized cities in the Jiangnan region of China share certain similarities in terms of historical development, geographical environment, cultural background, and the characteristics of the population they serve. As a typical small-to-medium town in Jiangnan, Yixing City presents representative, urgent, and significant resilience issues. Using Yixing as a case study to develop a resilience assessment framework for its living streets could provide valuable insights for other small and medium-sized cities in the Jiangnan region. Yixing is a historically rich town with a population of approximately 1.3 million. It is located in the southwest of Jiangsu Province and is at the geometric

Fig. 1 Conceptual schematic diagram of living streets.

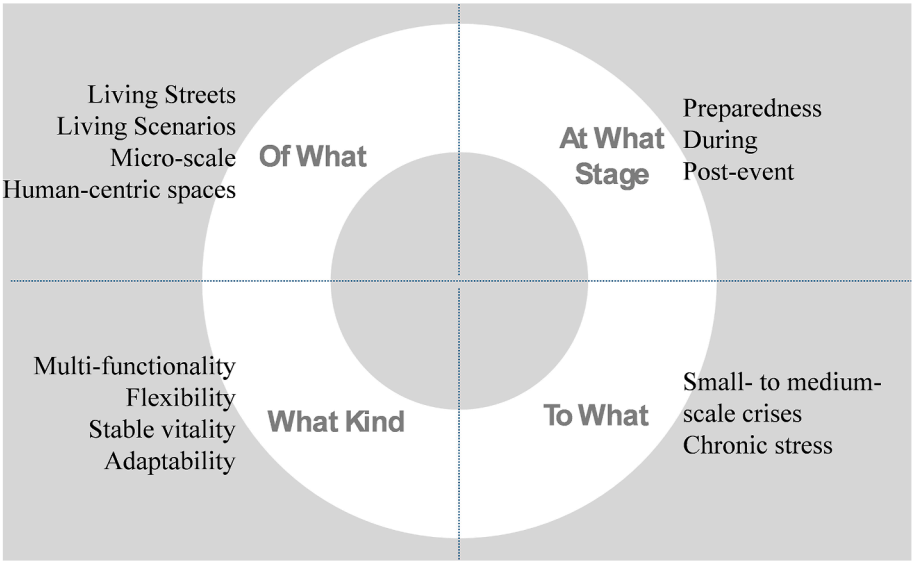

Fig. 2 Scope diagram of resilience research on living streets.

center of the Shanghai-Nanjing-Hangzhou triangle. It boasts a favorable geographic location and active economic development. In recent years, leveraging its abundant natural resources and cultural heritage, Yixing has gradually become one of China's most economically powerful county-level cities, with strong potential for promoting regional interconnectivity. Its living streets reflect common characteristics of small and medium-sized cities in Jiangnan, including pleasant scale, flexible spatial forms, rich cultural heritage, and a mixed function serving community needs (Fig. 3). However, they also face challenges such as outdated spatial facilities that require urgent updates, complex stakeholder involvement, and insufficient consideration of future resilience in the face of change.

3. Methodology

The research design is divided into four main stages: field survey, literature review, expert survey, and pilot testing (Fig. 4). 1) Initially, the dimensions obtained through participatory and non-participatory observation and interviews formed the first and second-level indicators of the initial evaluation framework. These also provided key search terms and focus areas for the subsequent phase. 2) In the literature review phase, we focused on identifying articles related to resilience assessment frameworks that address these aspects. We employed the SPIDER model to select relevant studies, extracting and categorizing the indicators from the selected literature while eliminating

Fig. 3 Location of Yixing City and characteristics of its living streets.

redundant ones. The selected indicators constitute the initial evaluation framework, which forms the questionnaire used for the Delphi method. 3) Subsequently, two rounds of Delphi surveys were conducted to gain experts' consensus on the evaluation framework. 4) Finally, pilot tests were conducted in 4 cities to demonstrate the tool's usability and effectiveness. All participants in the study were voluntary, and they signed an informed consent form.

3.1. Field research findings: core manifestations of resilience deficits

During the observation and analysis phase, we conducted participatory and non-participatory observations in Yixing. Participatory observation provided insights into the practical deficiencies in the resilience of street spaces from the perspectives of users and managers, such as the single functionality of spaces, short-term vitality, and operational deficiencies. Meanwhile, non-participatory observation took a more objective approach, recording the streets' physical structure and functional zoning to identify the root causes of resilience problems in living streets. We examined whether living streets exhibit sustained resilience across different periods, seasons, and weather conditions. In exploring key resilience issues, we also interviewed a few residents and street managers, focusing on the relative stability of street usage and the flexibility of operational management. Through four rounds of field research in 2024 (detailed in Appendix A), we identified the core manifestations of resilience deficits in four main dimensions: spatial and environmental, social and cultural, street economy and time dimension.

In addition, a broader study was conducted, collecting secondary data from similar small and medium-sized cities in the Jiangnan region, including cities such as Jiangyin, Jingjiang, Nantong, Changshu, Gaoyou, Taixing, and Xinghua (detailed in Appendix B). The living streets in these cities exhibited similar resilience deficiencies, confirming the representativeness and systematism of the identified issues. These findings formed the basis for subsequent literature reviews and the construction of the evaluation framework (Fig. 5).

3.2. Literature review findings: the first evaluation framework

To explore the specific factors affecting the resilience of living streets across the aforementioned dimensions, we searched for relevant articles from five major search engines: CNKI (China National Knowledge Infrastructure), Scopus, Web of Science, JSTOR, and Taylor & Francis. The objective of the literature review was to examine the intersection of micro-resilience and the development of living streets and to extract specific indicators for evaluating the resilience of living streets in small and medium-sized cities in the Jiangnan region. Based on the research objectives and previous in-depth insights into the core dimensions of sample issues, we primarily drew from studies on community resilience (Collier et al., 2013), urban spatial resilience in small and medium-sized cities, Individual and collective resilience supported by space environments (Dai et al., 2023), as well as resilience in social, cultural, operational management aspects. To ensure methodological rigor, we used the SPIDER model to define the criteria for including and excluding literature, which helped refine the evaluation framework, Specific literature search formulas and SPIDER settings are provided in Appendix C. Ultimately, 28 relevant papers were selected (Fig. 6). We extracted, summarized, and categorized the indicators they discussed, incorporating them into the pre-defined primary and secondary indicators, modifying some descriptions where necessary, and preliminary constructing the tertiary indicator section of the multi-dimensional assessment framework for street

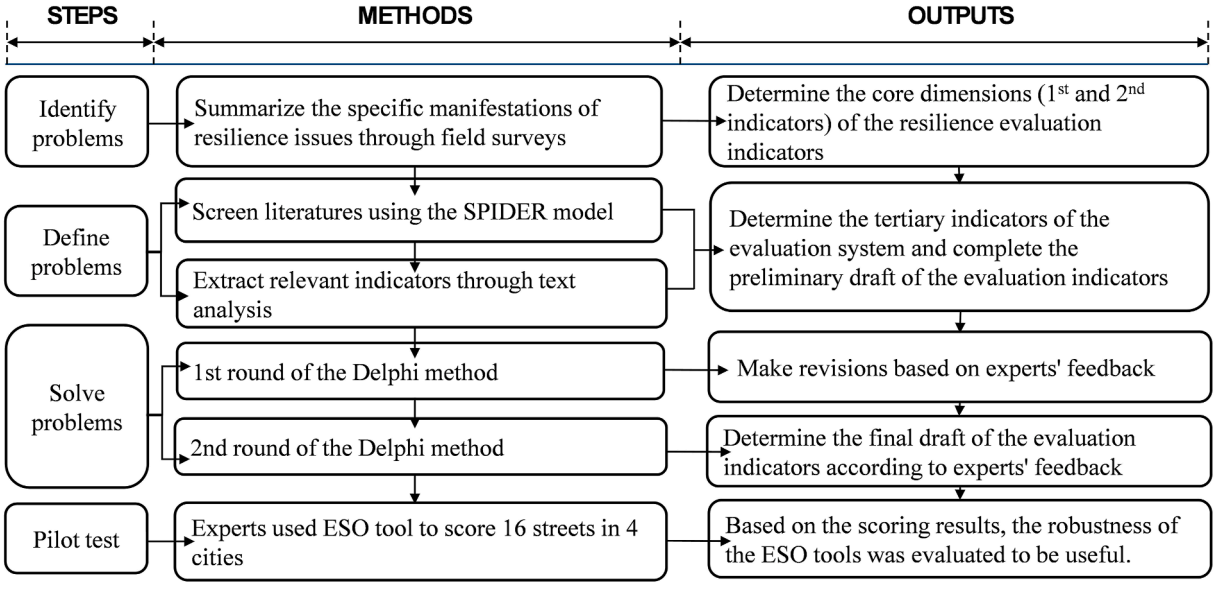

Fig. 4 Research flow chart.

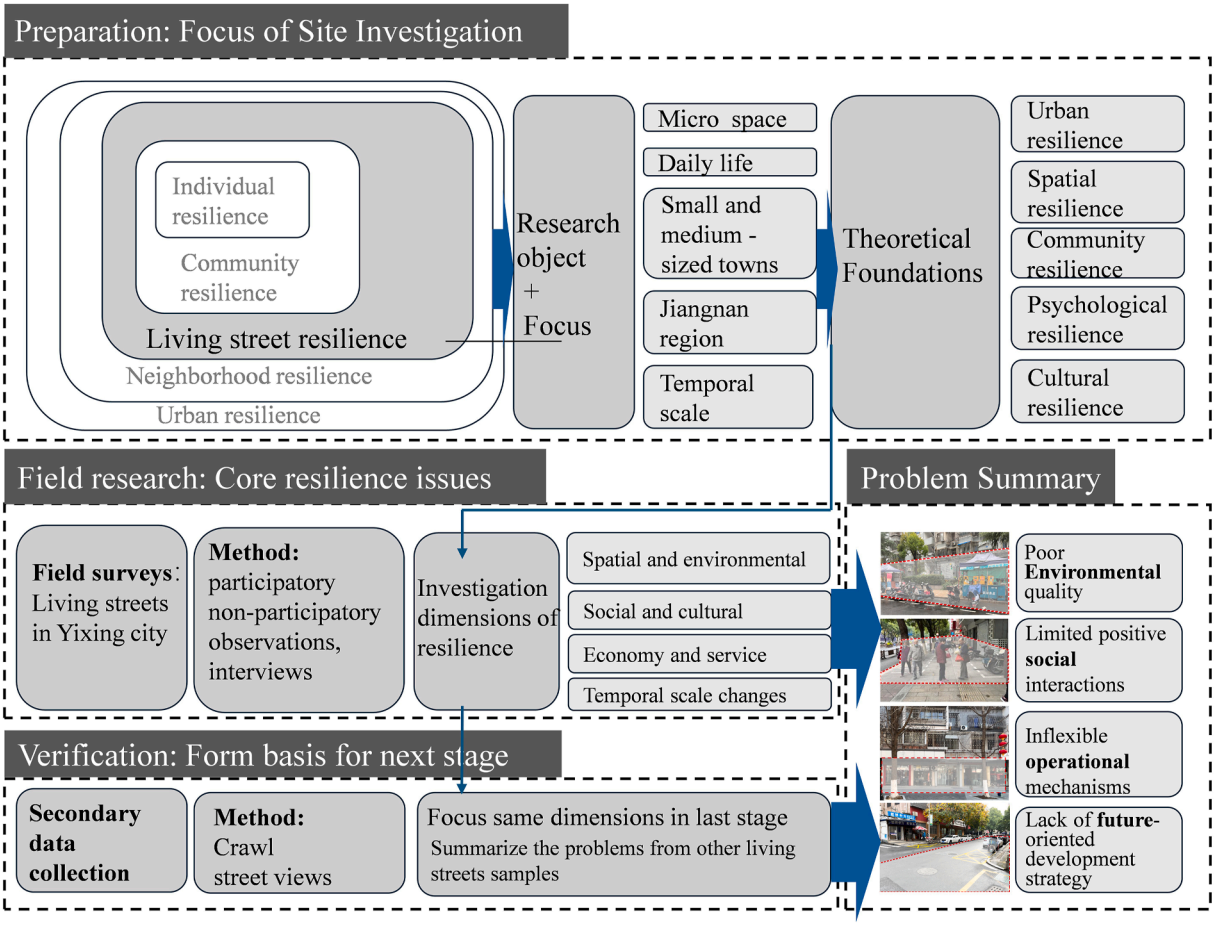

Fig. 5 Manifestations of insufficient resilience of living streets.

resilience (Table 1). This provided a theoretical foundation for subsequent expert surveys and practical application. At this point, the first version of the Delphi questionnaire was completed.

3.3. Delphi study

This study utilized the Delphi method to analyze and refine the resilience indicators for living streets. The Delphi method is a systematic approach that relies on expert opinions to address complex issues where consensus is difficult to achieve (Brady, 2015). The primary advantage of this method lies in its ability to progressively reduce discrepancies in expert opinions through at least two rounds of anonymous surveys, ultimately reaching a consensus (Okoli and Pawlowski, 2004). To collect data, we developed a survey using the "Wenjuanxing" platform, completing two rounds of surveys between October and December 2024.

The expert group comprised 20 participants selected based on their academic or professional practice expertise. The inclusion criteria were as follows: participants should be professors or researchers in design, urban planning, sociology, economics, environmental science, or related fields or professionals with over five years of experience in the development and spatial transformation of small and medium-sized cities. Official invitations and survey questionnaires were emailed to the 20 experts, including a detailed explanation of the research background and key terms. Nineteen experts responded to the invitation, and eighteen experts participated in the two survey rounds. The response rate for the expert consultation was 90 %, which is considered a high level of participation (Gordon, 1994).

Considering the research context in China, all participants were Chinese nationals. Among the 18 participants, 11% held bachelor's degrees, and the rest held master's degrees or higher. Regarding professional titles, 22% were professors, 39% were associate professors, and the remaining participants were researchers and other professionals. The demographic characteristics of the experts are shown in Table 2. The average work experience of the experts was 15 years, reflecting their deep understanding and authority in the field. The experts' authority coefficient (Cr) was calculated based on their self-assessment of familiarity with the survey questions, yielding a Cr value of 0.84. A Cr value greater than 0.70 indicates high reliability in expert consultation (Donabedian, 1979), suggesting that the results of this expert consultation are highly authoritative.

3.3.1. First-round Delphi procedure

The first round of the Delphi online survey was conducted from October 9 to October 22, 2024. The survey consisted of two sections: (1) indicator evaluation and (2)

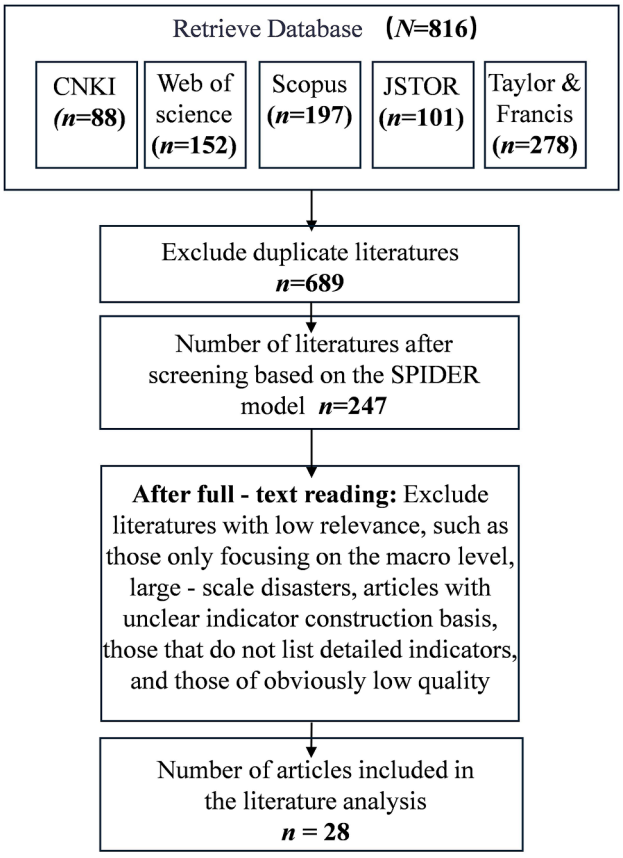

Fig. 6 Literature screening process diagram.

demographic information collection. Participants were instructed to evaluate whether existing indicators within each dimension required deletion, modification, or supplementation. Additionally, experts assessed the applicability and importance of three-tiered indicators using a 5-point Likert scale (1 = Not Important, 5 = Very Important). Open-ended feedback on the relevance and clarity of the indicators was also solicited to refine the framework.

3.3.2. Second-round Delphi procedure

Drawing on insights from the first round, the survey instrument was revised, and a second Delphi round was administered between October 28 and December 2, 2024. This phase aimed to present aggregated results from the initial round and re-evaluate the relevance of modified resilience indicators and dimensions to achieve expert consensus. Furthermore, the resilience assessment tool scale was finalized during this stage.

3.4. Pilot testing

To validate the tool, living streets across four representative small- and medium-sized cities in the Jiangnan region were selected for pilot testing. The objective was to evaluate the effectiveness of the ESO tool in diverse urban contexts. One tool developer and two urban renewal experts conducted field assessments under standardized weather conditions. The ESO tool employs a 5-point Likert scale (1 = Low Resilience, 5 = High Resilience) to quantify indicators across three resilience dimensions. The detailed ESO tool is provided in Appendix D. Each expert independently allocated 30 min per street to score indicators through participatory and non-participatory observation. Open-response sections allow experts to note ambiguities or challenges in indicator assessment. Total scores (summed item scores) and inter-rater reliability were analyzed using SPSS software, applying a two-way random effects model with absolute agreement consistency.

4. Data analysis and results

Data from the Wenjuanxing online platform were exported to SPSS for analysis. Key metrics included expert engagement coefficients, authority scores, consensus levels, and indicator mean values. For the first Delphi round, descriptive statistics (mean, maximum, minimum, standard deviation, and coefficient of variation [CV]) were calculated following methodology (Von Der Gracht, 2012). The framework was iteratively revised based on expert feedback and statistical outcomes, with subsequent rounds repeating analytical steps until achieving statistically significant consensus ($p < 0.05$).

4.1. First round expert consultation

The level of consensus among experts is typically expressed using Kendall's W coefficient, which measures the agreement between experts. The range of W is from 0 to 1, with higher values indicating more substantial agreement and consistency (Abdi, 2007). In the first round, the Kendall's W coefficient was $W = 0.368$. Generally, $W < 0.4$ indicates significant disagreement among experts, and consensus has not been reached (Cheng et al., 2010). Therefore, further optimization and refinement of the indicator framework were necessary.

The average values were used to represent the concentration of expert opinions. At the same time, the standard deviation and coefficient of variation (CV) reflected the dispersion of expert opinions (Han et al., 2017). A smaller CV indicates greater consensus among experts. The statistical results showed that the average values of the indicators ranged from 2.38 to 4.69, with standard deviations ranging from 0.37 to 0.77, and all CV values were less than 0.25. This suggests that a preliminary consensus was reached among experts on the first version of the indicators. CV values also revealed that among the secondary indicators, "Economic and Service Resilience" had a relatively high CV, as some experts felt that the description of economic resilience was too broad. The Third-level indicators such as "Intersection Spacing Distance", "Smart Infrastructure Level", and "Flexibility of Functional Zoning" had lower average values (less than 4.00), suggesting divergent understandings among experts. Most experts expressed a high degree of agreement with the secondary indicators under Social and Cultural Resilience. However, some tertiary indicators had lower average values, indicating that further refinement in their categorization and definition is needed.

Expert feedback from open-ended questions (Table 3) informed critical refinements to the resilience framework. The original "Economic and Service Resilience" dimension

Table 1 Sources of resilience indicators for living streets in small and medium-sized cities in the Jiangnan region.

First—level indicators	Secondary indicators	Tertiary indicators
Spatial and environmental Resilience (Rashidfarokhi and Danivska, 2023; Wang et al., 2023) (Mainly focusing on the ability of the physical space characteristics of streets and natural environmental factors to adapt to changes)	Morphological structure (Sharifi, 2019)	Effective width of sidewalks (Ros-McDonnell et al., 2024)
		Intersection spacing (Kapucu and Garayev, 2013)
		Aspect ratio of streets
		Side - facade continuity (Sharifi, 2019)
	Natural Ecology (Braubach et al., 2017)	Greening coverage rate (Forde et al., 2024)
		Rainwater infiltration rate (Cutter et al., 2008)
		Coverage rate of recycling facilities (Mamashli et al., 2021)
		Coverage rate of clean energy facilities (Berkes and Turner, 2006; Premier et al., 2023)
		Biodiversity (Goh et al., 2024)
	Functional facilities (Sádaba et al., 2024)	Accessibility of emergency shelter spaces (Sharifi, 2016)
		Intelligentization level of infrastructure (Zhou et al., 2021)
		Multi - functionality of street facilities (Liu and Liu, 2023)
		Durability of street facilities flexibility of functional zones (Elewa, 2019)
		Balance of service facility distribution (Dai et al., 2023)
		Completeness of pedestrian and cycling supporting facilities coverage rate of barrier - free facilities (Lanza et al., 2025)
Social and cultural resilience (Saja et al., 2019) (Mainly referring to the ability of streets to maintain their social structure and cultural characteristics stable, and enhance residents' sense of identity and cohesion when facing social changes and other challenges)	Social interaction (Kwok et al., 2016)	Diversity of street activities (Simpson et al., 2019)
		Duration of street activities (Champlin et al., 2023)
		Participation rate of street activities (Saja et al., 2019)
		Support degree of social network (Feng et al., 2022)
	Publicity and education (Fu and Zhang, 2024)	Emergency safety education (Ludin et al., 2019)
		Environmental protection and health education
		Mental health education (Richardson and Waite, 2002)
	Cultural recognition and inheritance (Ungar, 2014)	Shared values (Saja et al., 2019)
		Protection and inheritance of historical resources
		Continuation of local characteristics (Steiner and Atterton, 2015)
Economic and service Resilience (Wang et al., 2023) (mainly referring to the ability of streets to continuously develop through flexible management mechanisms when facing various internal and external changes during daily operation and long-term development)	Service and management (Fisher et al., 2012)	Flexibility of operation and maintenance mechanisms (Kourtit et al., 2022)
		Synergy of management organizations (Yildiz et al., 2017)
		Timeliness of information dissemination and early warning (Saja et al., 2019)
		Residents' participation in planning and decision making (De Carli, 2018)
		Digital management platform for streets

Table 1 (*continued*)

First—level indicators	Secondary indicators	Tertiary indicators
		(Zhou et al., 2021)
	Commercial operation (Erkip et al., 2014)	Diversity of street-side business formats (Erkip et al., 2014)
		Diversity of street-side business formats (Wang et al., 2023)
		Innovativeness of street-side merchant models (Andres and Round, 2015)

was redefined as "Operational and Management Resilience", emphasizing micro-level street services and business operations. Spatial-environmental indicators were expanded to integrate place-specific elements, such as traditional building materials and facade aesthetics, aligning with Jiangnan's historical-cultural context. Key additions—including perceived safety metrics and native plant ratios—enhanced environmental stability, while socio-cultural indicators incorporated localized social support networks and cultural continuity. These adjustments ensure the framework addresses both systemic vulnerabilities and residents' lived experiences, bridging technical rigor with contextual relevance to guide actionable urban renewal.

4.2. Second round expert consultation

The second round of the Delphi survey was based on the feedback from the first round, during which the evaluation framework was revised, and the tertiary indicators were clarified to improve expert consensus. The revised framework and first-round results were re-presented to the original expert panel. Kendall's W coefficient rose to 0.441 in this phase, reflecting more substantial consensus and confirming the reliability of outcomes, thereby eliminating the need for additional consultation rounds. Furthermore, the Coefficient of Variation (CV) (calculated as CV = (SD/M) × 100%) ≤ 18% was used to determine the retention of indicators. Specifically, the average scores for the three primary indicators were above 4.6, the average scores for the eight secondary indicators were above 4.5, and the CV for all 37 tertiary indicators was less than 0.20, as shown in Table 4. Five indicators—Functional Facilities, Social Interaction, Education on Resilience, Cultural Identity and Heritage, and Services and Management—achieved full-score rates exceeding 80%, demonstrating strong expert endorsement. Experts unanimously affirmed the model's capacity to evaluate living street resilience in Jiangnan's small- and medium-sized cities and its applicability to practice. Although minor suggestions for clarifying indicator descriptions emerged, no substantive revisions were required. The finalized resilience evaluation system comprised three primary, eight secondary, and 37 tertiary indicators (Table 4).

Table 2 Participant information table.

Sample information	Item	Number of people	Percentage (%)
Gender	Male	12	67
	Female	6	33
Age	Under 30	2	11
	31—40	3	17
	41—50	5	28
	51—60	6	33
	Over 60	2	11
Educational background	Bachelor	2	11
	Master	7	39
	PhD	9	50
Occupation	University professor	4	22
	Associate professor	7	39
	Researcher	2	11
	Related practitioners	5	28

4.3. Development of the ESO tool for living streets in Jiangnan region, China

The resilience evaluation tool ESO was developed by assigning weights to indicators through a systematic process grounded in expert consensus. First, each indicator level's mean scores from expert ratings were calculated to reflect their relative importance. These scores were normalized to ensure proportional weight distribution across the hierarchical framework. The results show that the weights for "Spatial and Environmental Resilience," "Social and Cultural Resilience," and "Operational and Management Resilience" are 0.325, 0.345, and 0.330, respectively. Furthermore, the weights for other secondary and tertiary indicators are shown in Fig. 7.

4.4. Pilot testing

The pilot testing aimed to validate the living street resilience assessment tool's operational efficacy and inter-rater consistency. We selected 16 representative living streets across four small- and medium-sized cities in the Jiangnan region (Fig. 8) for on-site evaluations under standardized environmental conditions. Three evaluators assessed each street to ensure methodological objectivity.

We calculated inter-rater reliability (IRR) using a two-way random-effects intra-class correlation coefficient (ICC) with absolute agreement to ensure tool robustness (Okoli

Table 3 Summary of opinions from some experts.

Summary of opinions	Question number	Experts' opinions
Indicator addition	Q8	Does the morphological structure of streets lack[a] content related to the facades of buildings along the street? [a]
		Does the aesthetic harmony of street colors, in terms of its impact on residents' psychology, promote resilience?
		Where is spatial safety reflected?
		Do native plants affect environmental resilience?
		How to consider the psychological resilience of different types of people?
		Can a dimension of personal psychological perception be added? [a]
	Q12	Does publicity and education take local cultural education into consideration? [a]
Indicator modification	Q4	Economic resilience is relatively macro-level and can be revised and refined. [a]
	Q8	The development of clean energy can promote the application of recycling facilities, and these two can be combined.
		Distribution equilibrium is like accessibility.[a]
		The flexibility of functional zoning may be subject to inconsistent interpretations.
		The degree of cultural identity may need to be more specific.
		The continuation of local characteristics can be specified in detail.
	Q16	Could add a brief description to the tertiary indicators.
Indicator deletion	Q5	The impact of intersection intervals may be relatively small.
	Q16	The residents' participation in planning decisions overlaps with the participation in activities. [a]
		Does the digital management platform for streets fall within the category of intelligent facilities?

[a] Occurs more than twice.

and Pawlowski, 2004). ICC values > 0.8 (excellent consistency) were achieved for 78% of indicators, confirming high rater alignment. The complete analysis results are shown in Table 5. For indicators with ICC < 0.8, scoring guidelines were refined to clarify ambiguous descriptors.

5. Discussion

Through the interlinked processes of indicator exploration, consultation, confirmation, and testing, we developed the ESO, a resilience assessment tool for living streets in small and medium-sized cities in the Jiangnan region. The ESO tool is structured around three primary dimensions, the environmental, social, and operational dimensions, and encompasses eight secondary dimensions and 27 indicators in total. Data from Delphi surveys and field-based pilot testing demonstrate the tool's theoretical robustness and practical reliability. The ESO tool also offers a scalable framework for enhancing resilience in other micro-scale urban spaces. It is not confined to a specific city and can be locally adapted to fit varying contexts.

5.1. Comparative synthesis and applicability of the ESO tool

The ESO tool delves into the resilience of living streets from a spatial perspective. It encompasses social functional dimensions, thereby supporting the multi-faceted resilience of people, activities, and objects that these spaces accommodate. Sharifi (2019) highlighted that street design features such as width, the design of street edges, and intersection density significantly influence resilience. The ESO tool likewise emphasizes the streets' physical features and supplements social culture and street operation. While certain factors are crucial for overall resilience, the ESO tool primarily focuses on the micro-level, excluding street network topology. Research by Naghibi et al. (2025), which also focuses on the resilience of small-scale public spaces, emphasizes the importance of space flexibility, diversity of planting and activities, which our research has confirmed. Regarding practical applicability, the ESO tool refines the conceptual framework for living streets resilience proposed by Liu and Liu (2023). Guided by expert consensus, abstract and non-quantifiable indicators were excluded, emphasizing exploring micro-level indicators that can be directly translated into actionable interventions and rapid pilot projects.

5.2. Integrating spatial precision into resilience planning

The ESO tool balanced functional stability, structural form, and ecological harmony in spatial and environmental dimensions. The secondary indicator of "Functional Facilities" (Average $= 4.47$) is considered the most significant within the spatial and environmental resilience domain. This is consistent with the findings of many studies on community resilience (Sharifi, 2016; Fu and Zhang, 2024). Among all the tertiary indicators, the "Rainwater Infiltration Rate" (Average $= 4.75$, CV $= 0.09$) was unanimously recognized by experts as a core factor influencing micro-resilience. This might be because it adapted to the humid and rainy climate in the Jiangnan region, providing a foundation for the stability and durability of the space. In the pilot test, "Natural

Table 4 Complete resilience evaluation framework with descriptive statistics and consensus metrics.

First level indicators	Second level indicators	Third level indicators	Average	Standard deviation	CV
Spatial and environmental resilience	Morphological structure	Effective width of sidewalks	4.31	0.47	0.11
		Aspect ratio of streets	3.69	0.48	0.13
		Spatial structure for perceived safety	4.44	0.51	0.11
		Use of traditional building materials in harmony with nature	3.31	0.48	0.15
		Aesthetics of side facades	4.19	0.40	0.10
	Natural ecology	Greening coverage rate	4.43	0.51	0.12
		Rainwater infiltration rate	4.75	0.45	0.09
		Coverage rate of recycling facilities	4.19	0.40	0.10
		Coverage rate of clean energy facilities 0.150	3.94	0.68	0.17
		Biodiversity 0.165	4.31	0.60	0.14
		Proportion of native plant configuration	4.06	0.68	0.17
	Functional facilities	Inclusiveness of emergency shelter spaces	4.63	0.50	0.11
		Level of intelligent infrastructure	4.19	0.40	0.10
		Multi-functionality of street facilities	4.38	0.50	0.11
		Durability of street facilities	4.63	0.50	0.11
		Flexibility of functional zoning	4.25	0.45	0.11
		Balance of service facility distribution	4.44	0.63	0.14
		Completeness of supporting facilities for walking and cycling	4.69	0.48	0.10
		Coverage rate of barrier-free facilities	4.56	0.51	0.11
Social and cultural resilience	Social interaction	Diversity of street activities	4.63	0.50	0.11
		Duration of street activities	4.31	0.70	0.16
		Participation rate of street activities	4.44	0.63	0.14
		Support degree of social networks	4.69	0.48	0.10
		Cohesion of resident groups	4.38	0.50	0.11
	Publicity and education	Emergency safety education	4.25	0.45	0.11
		Environmental protection education	4.56	0.51	0.11
		Mental health education	4.69	0.48	0.10
	Cultural recognition and inheritance	Consensus on positive values	4.56	0.51	0.11
		Protection and inheritance of traditional buildings along the street	4.63	0.50	0.11
		Continuation of intangible local characteristics	4.50	0.52	0.12
Management and operation resilience	Service and management	Flexibility of operation and maintenance mechanisms	4.56	0.51	0.11
		Synergy of management organizations	4.75	0.45	0.09
		Timeliness of information dissemination and early warning	4.63	0.50	0.11
	Commercial operation	Innovation of business models of street-side merchants	4.31	0.48	0.11
		Diversity of business formats of street-side merchants	3.50	0.52	0.15
		Proportion of local merchants	4.63	0.50	0.11
		Operational stability of street-side merchants	3.50	0.51	0.15

Ecology" (ICC = 0.82) showed high consistency among experts, indicating that indicators' descriptions containing types, configurations, and coverage ratios can be effectively measured in resilience assessments.

5.3. Combining micro resilience with social functionality

Many studies have confirmed that social activities strengthen the support provided by social networks and can also serve as vital spiritual support during crises (Aldrich, 2012; Kourtit et al., 2022). Especially in small cities, where traditional family and local cultures are more potent, the close relationships among residents and a supportive, collaborative street atmosphere create the foundation for resilience (Ungar, 2016). This significance is also reflected in the expert ratings. On the other hand, targeted education can raise awareness about environmental protection, mental health, and other aspects, thereby enhancing the adaptability and recovery of residents and the region (Finnis, 2004). "Social and Cultural Resilience" holds the highest weight ($W = 0.345$), indicating its critical role. However, the lowest ratings for this aspect in the pilot test indicate that it might be a focus for future urban renewal.

In existing resilience research, economic resilience has been a more macro-level and general concept (Kourtit et al., 2022). Since our study focuses on the micro perspective, many experts emphasized the need to refine the economic resilience indicators in the first round of expert consultations. After modifying it to "Operational and Management Resilience," the subsequent tertiary indicators focused more on the stability and innovation of service-oriented businesses on living streets. Micro-economic activities affect the street's economic vitality

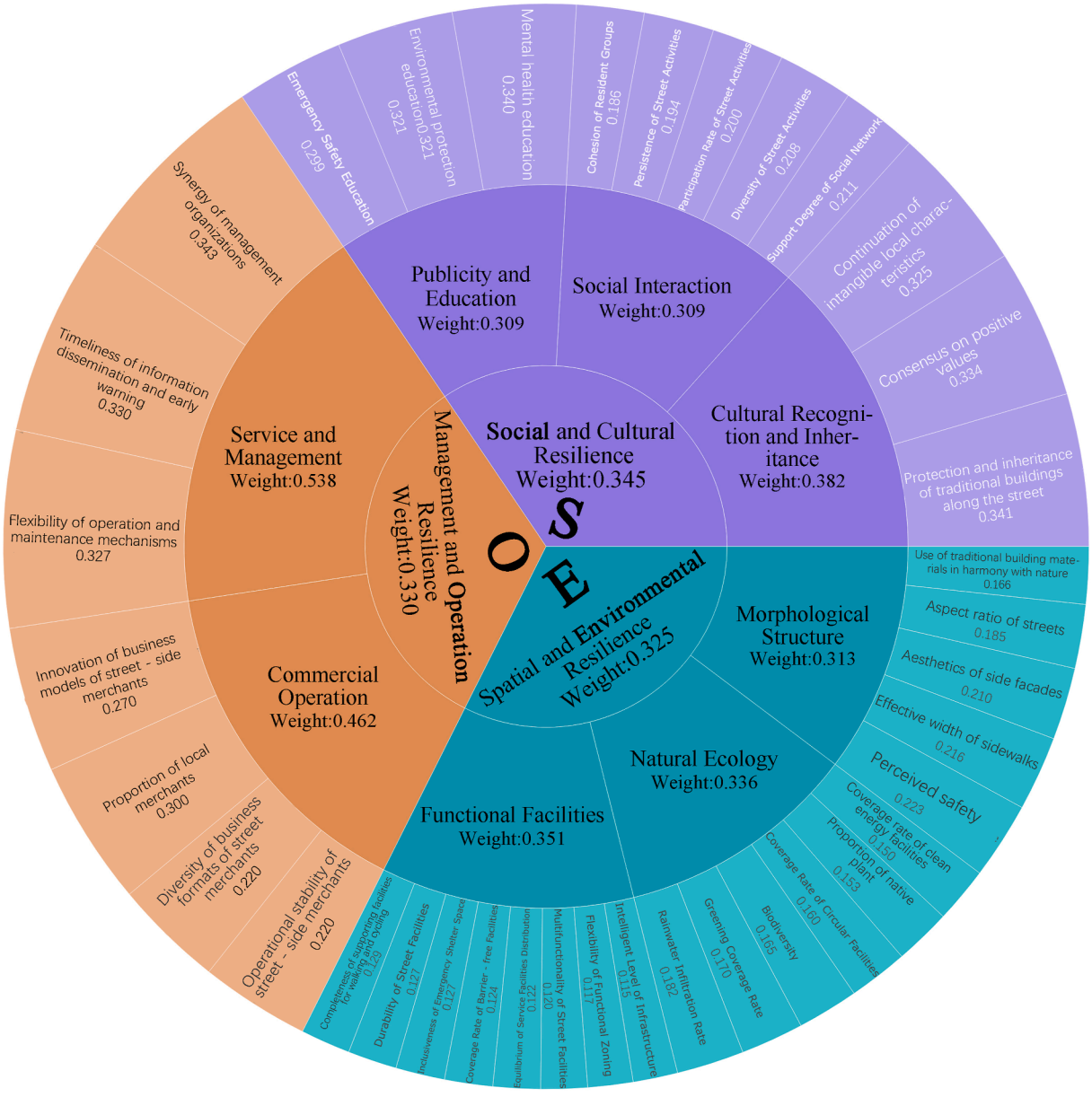

Fig. 7 Weight structure diagram of indicators at all levels of the ESO evaluation tool.

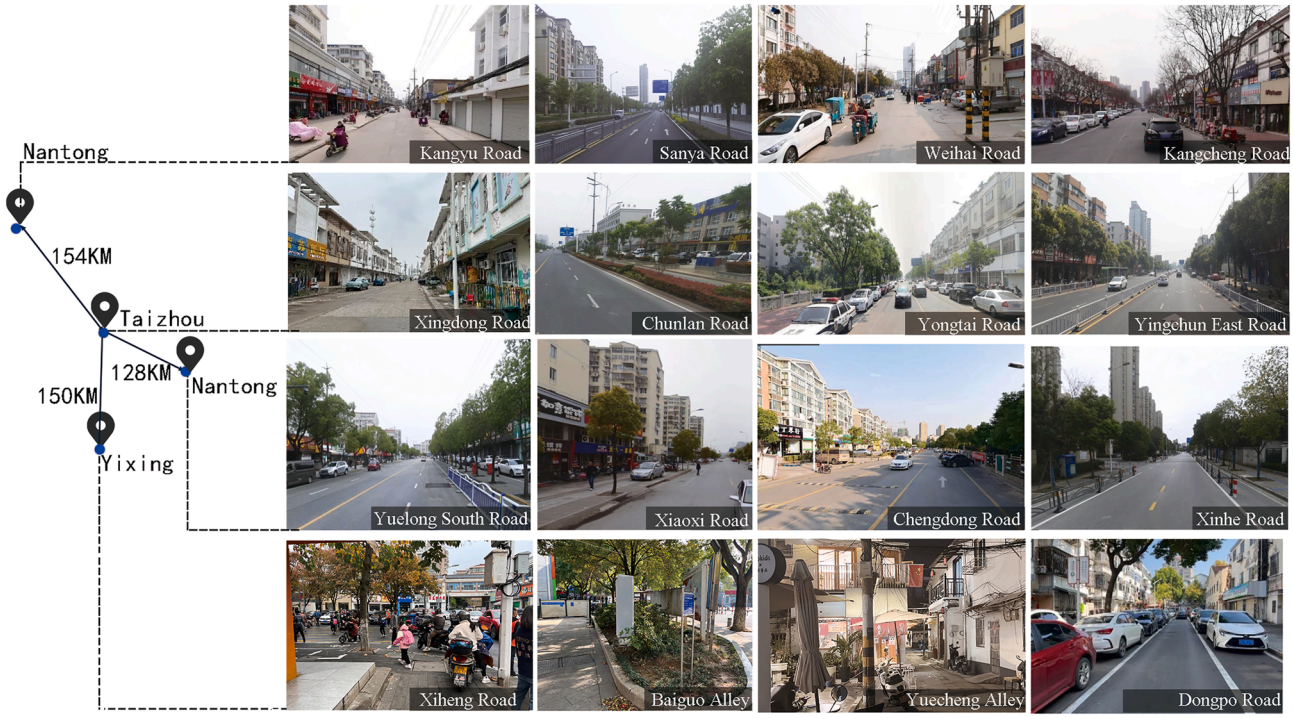

Fig. 8 Pilot testing of street view in four cities.

and residents' convenience, they are also key to maintaining community memory and neighborhood relationships, contributing to social cohesion. "Diversity of business formats" enhances the street's resilience when facing market fluctuations and changes in resident demands, enriching residents' lives and sustaining the vitality of the street (Annarelli et al., 2020). "Proportion of local merchants" can contribute to the street's self-sufficiency in exceptional circumstances. These micro-level insights form the foundation and the resilience of the urban commercial ecosystem.

5.4. Expanding the Jiangnan region toward broader regional practices

The discovery of indicators such as "Rainwater Infiltration Rate", "Aesthetics of side facades", "Traditional Building Material Usage" and "Native Plant Proportion" address the water-town features and rich heritage of many small and medium-sized cities in Jiangnan. These metrics reflect the region's longstanding ecological adaptability (Xiao and Yuizono, 2022), enhancing macro-resilience while preserving local cultural characteristics and ecological continuity. Cultural memories in streets can effectively connect residents' emotions, enhancing their sense of well-being, belonging, and cohesion, thus indirectly promoting the achievement of long-term stability resilience (Donelli et al., 2021; Panter-Brick, 2015). These regional-specific indicators are often insufficiently addressed in research focused on large cities or generic studies, which also have the potential to provide inspiring insights for future explorations of resilience adaptation in other regions.

5.5. Limitations and future research directions

Three key limitations require attention. First, as the study was confined to Jiangnan, Chinese experts were exclusively chosen, and both the investigation and the pilot test were

Table 5 Pilot test results of the ESO tool.

Primary dimension	Descriptive statistics			Interrater reliability	
	Median	IQR	Min–Max	Intra-class Correlation Coefficient (ICC)	95%CI
Morphological structure	16	3	13–20	0.80	0.67–0.89
Natural ecology	15	3	12–18	0.82	0.70–0.91
Functional facilities	20	4	16–24	0.78	0.64–0.88
Social interaction	12	2	10–14	0.81	0.69–0.90
Propaganda and education	6	1	5–7	0.85	0.73–0.93
Cultural identity and inheritance	7	2	5–9	0.79	0.66–0.88
Service and management	9	2	6–12	0.83	0.71–0.91
Commercial operation	10	3	7–13	0.81	0.69–0.90
Total score	105	12	85–125	0.81	0.69–0.90

conducted in the Jiangnan region, so its regional characteristics may limit its generalizability in other regions. Second, while the Delphi method ensured theoretical rigor, it may introduce subjective interpretations of indicators. Variations in experts' interpretations and weightings of indicators across dimensions were observed. Particularly along generational lines, senior experts prioritized age-friendly indicators, whereas younger counterparts emphasized dynamic resident participation and street activities. While these generational perspectives enriched the study's analytical breadth, potentially limiting the representativeness of specific metrics. Third, pilot testing validated the ESO tool's soundness. However, since it is still in the early stages of the research and the number of cities involved in the test is limited. Different focuses may exist in regions with different socio-economic conditions or cultural traditions. During the research process, efforts were made to be as comprehensive as possible, but some aspects were inevitably overlooked, which may limit the comprehensiveness of the ESO tool. With the development of cities and social changes, new problems and needs are likely to emerge continuously. Therefore, the ESO tool requires continuous updating and improvement.

Given these limitations, future research could further test this tool in other cities within the Jiangnan region. The ESO tool should be selectively updated in accordance with the dynamic nature of the issues at hand to enhance its applicability. Moreover, considering its expansion to other regions, some indicators could be adjusted to apply to other types of cities, such as coastal and mountainous cities. Future research could explore how this tool can be employed in different types of living streets across China and beyond, especially in the context of diverse urban renewal projects. Such testing will allow for a deeper understanding of the tool's adaptability and relevance to cities with distinct economic, social, and cultural contexts. The iterative application of the tool in real-world settings will enable refinement and improvement, ensuring that it remains applicable and reliable in guiding urban resilience strategies. Additionally, expanding the research perspective, future research should adopt a multi-stakeholder approach to integrate resident perspectives, conduct comparative studies across cultural and demographic contexts, and embed the framework in urban renewal projects for iterative refinement. Interdisciplinary collaboration, incorporating urban design, sociology, and environmental science, will further advance micro-resilience strategies.

6. Conclusions

This study pioneers a resilience evaluation framework tailored to the unique socio-spatial fabric of living streets in Jiangnan's small and medium-sized cities. A hierarchical indicator system was developed, comprising three primary dimensions (spatial-environmental, socio-cultural, and operational management), 8 secondary and 37 tertiary indicators.

Theoretically, this research shifts focus to micro-scale and smaller urban contexts. It advances discourse by emphasizing localized cultural heritage, thematic education, resident participation, and adaptive street management, which are often overlooked in macro-scale studies. The micro-level lens identifies street-specific resilience needs precisely, bridging the gap between granular design interventions and broader urban strategies.

Practically, the framework leverages the inherent strengths of small-cities streets, functional diversity, tight-knit communities, and flexible governance. Indicators are operationalized as actionable design checklists, transforming vulnerabilities into opportunities. In renewal projects, the ESO tool can diagnose resilience deficits and guide targeted improvements, while in new developments, it ensures resilience is embedded from inception. By harmonizing theoretical rigor with practical applicability, this research enriches academic understanding and equips planners and policymakers with tools to cultivate resilient, vibrant streetscapes in Jiangnan and beyond.

Ethics statement

The authors declare that their Institutional Ethics Committee confirmed that no ethical review was required for this study. Written informed consent for participation was not required because all participants' data was anonymized before the statistical analyses were done.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foar.2025.05.013.

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