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Research article

Evaluation and obstacle analysis of sustainable development in small towns based on multi-source big data: A case study of 782 top small towns in China

Mingman Chen [a], Chen Chen [a], Chi Jin [b,*], Bo Li [d], Yingqing Zhang [c], Ping Zhu [a]

[a] School of Management Science and Engineering, Guizhou University of Finance and Economics, Guiyang, China
[b] Management in the Built Environment, Faculty of Architecture and the Built Environment, Delft University of Technology, Julianalaan 134, 2628BL, Delft, the Netherlands
[c] School of Business Administration, Guizhou University of Finance and Economics, Guiyang, China
[d] Department of Sociology, John F. Kennedy Institute for North American Studies, Freie Universität Berlin, Germany

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ABSTRACT

Evaluating the sustainable development level and obstacle factors of small towns is an important guarantee for implementing China's new-type urbanization and rural revitalization strategies, and is also a key path to promoting the United Nations Sustainable Development Goal 11 (SDG11). Traditional evaluation methods (such as Analytic Hierarchy Process, AHP, and Technique for Order Preference by Similarity to Ideal Solution, TOPSIS) mainly calculate the comprehensive score of each indicator through weighting. These methods have limitations in handling multidimensional data and system nonlinearity, and they cannot fully reveal the complex relationships and interactions within the sustainability systems of small towns. In contrast, the evaluation model combining Principal Component Analysis (PCA) and Catastrophe Progression Method (CPM) used in this study can better handle multidimensional data and system nonlinear relationships, reducing subjectivity in evaluation and improving the accuracy and reliability of the assessment results. The specific research process is as follows: First, based on the United Nations SDG11 framework, using multi-source big data, a theoretical framework and evaluation index system for the sustainable development of small towns suitable for the Chinese context were established. The impact of county-level factors on the sustainable development of small towns was also considered, and an entropy weight-grey correlation model was used to measure these impacts, resulting in a town-level dataset incorporating county-level influences. Secondly, the sustainability levels of 782 top small towns in China were evaluated using the comprehensive evaluation model based on PCA-CPM Model. Finally, an improved diagnostic model was used to identify obstacles influencing the sustainable development of small towns. The main findings include: 52.69% of the small towns have a sustainable development score exceeding 0.7255, indicating that the overall performance of small towns is at a medium to high development level. The development of small towns exhibits significant differences across regions and types, which are closely linked to county-level effects. Economic and social factors are the main obstacles to the sustainable development of small towns, and the impact of these obstacles intensifies from the eastern to the central, western, and northeastern regions. This study provides valuable insights for policymakers and scholars, promoting a deeper understanding of the sustainable development of small towns.

1. Introduction

Small towns, as crucial connectors between urban and rural areas, have become indispensable components of the urban framework (Liu et al., 2020; Filipović et al., 2016). The United Nations Sustainable Development Solutions Network (SDSN) released the 9th edition of the Sustainable Development Report (SDR), indicating that global progress on the Sustainable Development Goals (SDGs) has stalled since 2020. By 2030, none of the 17 SDGs are expected to be achieved, with SDG 11 (sustainable cities and communities) particularly off track (Sachs et al.,

* Corresponding author. Julianalaan 134, 2628BL Delft, the Netherlands.
E-mail address: C.JIN-1@tudelft.nl (C. Jin).

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2024). By 2050, it is projected that 70% of the global population will reside in urban areas (United Nations, 2023). Rapid urbanization will lead to issues such as chaotic spatial development, excessive population concentration, energy shortages, and ecological degradation (Mahmoud and Gan, 2018). Cities will struggle to adapt quickly and address these challenges. Therefore, small towns are emerging as crucial engines for regional health and sustainable development, driving the progress of sustainable cities and communities.

Compared to large cities, small towns are seen as more sustainable urban forms (Mally et al., 2022), offering solutions for future urbanization and mitigating urban issues (Lin et al., 2023). Firstly, small towns typically have populations ranging from 5000 to 20,000 (Mayer and Lazzeroni, 2022; Atkinson, 2019), providing sufficient social interaction opportunities without overcrowding. Secondly, small towns face fewer issues with traffic congestion, environmental pollution, and crime, leading to a better living experience (Mainet, 2015). More importantly, small towns, as connectors of urban and rural resources (Zhang et al., 2024; Filipović et al., 2016), or as an urban-rural continuum (Mayer and Lazzeroni, 2022; Han et al., 2023), have significant advantages in balancing regional development (Mally et al., 2022), optimizing resource allocation (Hu et al., 2022), promoting rural employment (Yu et al., 2023), providing commercial services (Bogdański and Janusz, 2022), and advancing urban-rural integrated development (Wang and Ma, 2023; Liu et al., 2020). Additionally, small towns often possess unique natural heritage, ethnic cultures, and local industries (Liao and Yi, 2018; Jaszczak et al., 2024), demonstrating significant potential in preserving local character and uniqueness (Surekha, 2022).

Thus, exploring the pathways to achieve Sustainable Development Goal 11 (Sustainable Cities and Communities) from the perspective of small towns is both feasible and necessary. However, small towns currently face issues such as weak industrial foundations, lagging infrastructure and public services, and institutional constraints (Xiong et al., 2020; Gong et al., 2022; Aliaskarov et al., 2023), which severely impede the progress towards sustainable cities and communities. Evaluating the sustainable development level of small towns and identifying the obstacles are crucial steps (Kaimuldinova et al., 2024). Although the United Nations has set 15 specific indicators for SDG 11, these globally applicable indicators face challenges in implementation in certain regions or countries (Wang et al., 2024), particularly in China, with its multi-tiered administrative system and over 20,000 small towns (Tong et al., 2020).

To address these challenges, this study, guided by the United Nations (UN) SDG 11 framework and the key implementation measures outlined in China's National Plan for Implementing the 2030 Agenda for Sustainable Development, uses multi-source big data to establish a sustainable development indicator system and evaluation model for small towns in China. This provides rapid and accurate quantitative monitoring and assessment methods for the sustainable development of small towns and offers references for China's long-term sustainable development planning. The paper is structured as follows: Section 2 provides a literature review and theoretical framework. Section 3 outlines the materials and methods, including study area, data sources and methods. Section 4 presents the results and discussions, focusing on the sustainable development evaluation for 782 top small towns and an analysis of obstacles. Finally, Section 5 delves into the conclusions and policy implications.

2. Literature review and theoretical framework

2.1. Research on sustainable development of small towns

2.1.1. Sustainable development of small towns

The sustainable development of small towns should consider the economic, social, and environmental dimensions to achieve overall balance and growth (Ghalib et al., 2017; Caldatto et al., 2021; Kaimuldinova et al., 2024). For example, Nesticò et al. (2020) introduced a dataset of evaluation indicators for small towns that integrates social, economic, environmental, and historical architectural elements. Small towns are complex systems comprising subsystems of economy and industry (Gong et al., 2022; Aliaskarov et al., 2023), ecological environment (Yukhnovskyi and Zibtseva, 2019; Li et al., 2023), society and culture (Xiao et al., 2022; Krajnik et al., 2022; Kangshu, 2023), and infrastructure and public services (Tripathi, 2021; Yu et al., 2023).

Small towns possess the dual attributes of both "urban" and "rural" (Bański, 2021; Han et al., 2023). Their sustainable development continues urban concepts while respecting local characteristics and uniqueness (natural environment, historical culture, and biodiversity) (Mainet, 2015; Surekha, 2022). The uniqueness of small towns has led to multi-level development classifications (Senetra and Szarek-Iwaniuk, 2020; Han et al., 2022) and diverse sustainable development models, including agriculture-oriented characteristic towns (Hu et al., 2022), culture and tourism-led models (Ponomareva et al., 2020), and project-driven approaches (Shalina et al., 2021). Furthermore, factors such as industrial clustering and innovation (Wu et al., 2018; Liang et al., 2020), economic structure (Wang and Ma, 2023), regional integration (Demazière et al., 2024), policy and institutional innovation (Jaszczak et al., 2024), and social governance (Xiong et al., 2018; White, 2022) significantly enhance the sustainability of small towns.

The sustainable development of small towns can not only alleviate "urban diseases" and improve residents' living standards, but also achieve high-quality economic and social development (Filipović et al., 2016). It is a key pathway and important guarantee for implementing new urbanization and rural revitalization strategies. However, small towns in China are still underdeveloped, facing institutional, economic, social, and ecological barriers (Shen et al., 2018; Atkinson, 2019; Xiong et al., 2020; Gong et al., 2022; Aliaskarov et al., 2023), which significantly hinder the progress of sustainable urban and residential development. Furthermore, there are marked hierarchical and regional disparities in the development of China's small towns (Guo et al., 2014; Hu et al., 2022). Some small towns in northeastern and peripheral mountainous regions are smaller in scale and have singular functions, influenced by the siphon effect, leading to shrinkage or even disappearance (Tong et al., 2020; Liu et al., 2022). Conversely, small towns in developed eastern regions like Zhejiang and Guangdong, with advantageous geographical locations, accessible transportation, pleasant environments, and prominent characteristic industries, are emerging as new platforms driving industrial transformation and upgrading, the aggregation of nascent industries, and integrated urban-rural development (Wu et al., 2018).

2.1.2. Evaluation indicators and data for sustainable development of small towns

Sustainable development assessment indicators and data are crucial for evaluating sustainable development. In 2015, the United Nations established the Sustainable Development Goals (SDGs), comprising 17 goals, 169 specific targets, and 232 indicators (Gupta and Vegelin, 2016). However, these global and universal indicator systems face challenges in practical application, such as difficulties in data acquisition, lack of standardized methods, and poor data quality, mainly due to insufficient statistical data and institutional and practical foundations (Choi et al., 2016). Therefore, scholars often localize these global indicators (Nesticò et al., 2020; Koch and Krellenberg, 2018). For example, Almeida et al. (2018) developed a city sustainability evaluation system based on SDG 11, encompassing nine indicators across social, environmental, economic, and political dimensions. Cong et al. (2021) constructed a multi-layered urban livability sustainability evaluation system tailored to China's conditions, with 40 indicators aligned with the 17 SDGs, covering natural systems, human systems, residential systems, social systems, and support systems.

In data-scarce small town regions, developing localized indicator systems based on global sustainable development goals presents significant challenges. Currently, only a few scholars have attempted to construct sustainable development indicator systems for small towns using these frameworks. For instance, Ponomareva et al. (2020) based their small town development index system on the UN-Habitat City Development Index(CDI), covering infrastructure, waste collection and disposal, population health, education, and urban products. Most scholars construct indicator systems based on sustainable development dimensions. For example, Visvaldis et al. (2013) selected 15 key indicators from economic, environmental, and social dimensions to establish a foundational framework for small town sustainability. Senetra and Szarek-Iwaniuk (2020) selected 29 indicators from demographic, socio-economic, and spatial-functional dimensions to evaluate the development patterns of 28 small towns in Poland's Cittaslow network, finding that high economic activity and enterprise registration rates drive town development. Han et al. (2022) selected 16 indicators across industrial development, transportation location, social welfare, and resource potential to construct an evaluation system for small towns. These studies primarily rely on statistical yearbooks, in-depth interviews, and expert polls to collect data, but they still face challenges such as data accessibility and quality issues. Fortunately, the application of Geographic Information Systems (GIS) and open geospatial technologies in assessing and monitoring global sustainable development goal indicators has provided new support for obtaining certain indicators in small towns (Musango et al., 2020).

2.1.3. Evaluation methods of sustainable development of small towns

The Analytic Hierarchy Process (AHP) and the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) are classical evaluation models widely used in assessing the sustainable development of small towns. For example, Li et al. (2023) used the AHP method for ecological evaluation of small towns. Guo et al. (2014) employed the TOPSIS method to assess the development levels of small towns across various regions in China, providing a comprehensive understanding of their current development status and potential. Additionally, Xiong et al. (2020) combined Principal Component Analysis (PCA) and TOPSIS methods to systematically analyze 16 sample towns in southwestern China, revealing significant imbalances in development levels among different towns.

New evaluation models based on decision theory, constraint theory, and complex adaptive systems theory have also gained attention and application. For instance, Lin et al. (2023) utilized a hybrid multi-attribute decision-making model to evaluate the sustainable development potential of feature towns and identified key factors influencing their development. Hu et al. (2022) constructed a sub-constraint evaluation model under the Theory of Constraints to study the development of agriculture-oriented small towns, emphasizing sustainable development assessment under specific constraints, providing a new perspective for the development of agricultural small towns. Geng and Qiao (2018) employed the NK Fitness Landscape Model under Complex Adaptive Systems Theory to assess the development of small towns surrounding Wuhan City. This model simulates adaptability within complex systems, evaluating the development potential of small towns under different scenarios, offering new analytical tools and methodologies.

Additionally, the efficiency evaluation of small towns has garnered attention. Yin et al. (2021) used Data Envelopment Analysis (DEA) and Analysis of Variance (ANOVA) to measure the efficiency of 109 towns across seven counties in Jiangsu Province. Through quantitative analysis, they assessed the resource utilization efficiency of each town, providing data support for policy-making.

2.2. Research gaps

Evaluating the sustainable development of small towns is a complex and multidimensional process, encompassing economic, social, environmental, locational, and transportation aspects. Existing research provides valuable assessment tools and insights. However, there are still some shortcomings in data, indicators, and evaluation methods.

2.2.1. The lack of traditional statistical data and the difficulty in obtaining them

The data sources for evaluating the sustainable development of small towns primarily rely on traditional collection methods, such as statistical data (including statistical yearbooks, census data, and statistical reports), field survey data, and interview data (Tong et al., 2021; Stoica et al., 2020). Statistical data typically has fixed items and units, which limits the expression of evaluation content and detail. Especially at the town level and below, due to insufficient statistics, the description of the research subject is often incomplete. In China, statistical data on small towns is limited to the "China County Statistical Yearbook (Township Volume)" and decennial census data, with indicators including only basic data such as administrative area, registered population, and number of industrial enterprises. Field surveys and interview data commonly encounter problems related to extended durations and significant difficulties (Yu et al., 2023). Consequently, the completeness, accuracy, and timeliness of indicator data for the sustainable development of small towns are generally low, constraining the ability to perform a thorough, timely, and accurate evaluation (Han et al., 2022).

The United Nations emphasized in the "Sustainable Development Goals Report 2023: Special Edition" that accelerating data actions—including the monitoring and collection of non-traditional data, improving data quality and timeliness, and enhancing data innovation (focusing on the integration of multiple data sources)—is crucial for advancing the Sustainable Development Goals (United Nations, 2023). In the era of big data, the Internet and geospatial monitoring technologies can collect abundant multi-sourced data pertinent to urban sustainable development. Examples include web text data (Wang et al., 2021), nighttime light data (Zhang et al., 2022a), Points of Interest (POI) data[1] (Zhang et al., 2022b), land usage data (Sun et al., 2022), and digital elevation data (Gong et al., 2022). These substantial multi-source data cover multiple facets of small town sustainable development. Not only can they effectively reflect the comprehensiveness and timeliness of development dimensions of small towns, but they also enhance the accuracy in diagnosing the obstacles to the development of small towns, becoming an important means for comprehensively, promptly, and accurately evaluating the sustainable development of small towns. However, the current research still lacks sufficient application of these modern data technologies and has not yet fully realized their potential.

2.2.2. Lack of consideration of county-level effects in indicator construction

As Mayer and Lazzeroni (2022) point out, small towns are an urban–rural continuum, possessing both urban characteristics and retaining some rural traits. Under the concept of "borrowing size," small towns can leverage their close ties with larger cities to utilize urban resources and opportunities for their own development (Demazière et al., 2024; Meijers and Burger, 2022). In recent years, the Chinese government has introduced a series of policies to promote the sustainable development of small towns, including rural rejuvenation, urban-rural amalgamation, and comprehensive regional coordination. These policies highlight the pivotal influence of county development in steering and determining sustainable growth directions for small towns. For instance, the "Opinions on Promoting Urbanization Construction with Counties as an Important Carrier" issued in May 2022, emphasizes

[1] Points of Interest (POI) refer to specific locations that might be of interest to someone, usually in the context of navigation, travel, or geographic information systems. These locations can include landmarks, tourist attractions, businesses, public facilities, and natural wonders. They are commonly used in GPS navigation systems, mapping services, and location-based applications to help users find or discover places that are important or useful. POIs are integral to modern mapping and navigation technologies, providing critical data for directions, travel planning, and exploring new areas.

extending county-level infrastructure and public services to suburban rural areas and larger towns.

Although scholars have recognized the influence of county-level and higher regional levels (municipal areas) on the sustainable development of small towns (Yu et al., 2023; Tong et al., 2020), integrating county-level impacts into the sustainable development indicators of small towns in quantitative analyses remains challenging. For instance, Tong et al. (2021) incorporated county-level and town-level dimensions into the same indicator system to reflect county-level factors' influence on the shrinkage of small towns. However, this approach failed to effectively identify the specific extent and scope of county-level impacts on various dimensions of small towns. Similarly, Han et al. (2023) established interaction indicators from the perspective of rural-urban interactions, such as spatial connections and economic ties, but did not fully capture the extent of county-level influence.

2.2.3. Evaluation methods are insufficient in analyzing the internal connections of sustainable development systems

The sustainable development of small towns is a complex, multidimensional system encompassing natural resources, ecological environment, economy and industry, location and transportation, infrastructure, and policy institutions (Han et al., 2022; Nesticò et al., 2020; Kaimuldinova et al., 2024; Mainet, 2015). A scientific and effective evaluation method must consider the integration of these factors and fully account for the internal connections and interactions within the system.

In recent years, scholars have recognized the limitations of traditional evaluation methods (such as AHP and TOPSIS) in analyzing the internal relationships and interactions within small town sustainable development systems. Consequently, they have begun to incorporate advanced theories and methods, such as decision theory, constraint theory, and complex adaptive systems theory. Examples include the NK model (Geng and Qiao, 2018) and Decision-Making Trial and Evaluation Laboratory (DEMATEL)-based Network Analysis (DANP) (Lin et al., 2023). These methods not only simplify multidimensional data but also reveal the intrinsic relationships and relative importance of various factors, helping researchers and decision-makers better understand how different factors interact. Although these methods still do not fully capture the complexity, structure, and variability of small town development systems, they offer valuable methodological explorations for evaluating sustainable development in small towns.

Therefore, for a more thorough and detailed systematic investigation into the sustainable development of small towns in China, this study, guided by the UN SDG 11 framework and the key implementation measures outlined in China's National Plan for Implementing the 2030 Agenda for Sustainable Development, concentrates on 782 top towns in China, aiming to assess their sustainable development levels and identify the obstacles hindering their growth. Firstly, to overcome the challenges of incomplete and outdated data in small towns, we rely on multi-source big data. This dataset includes natural geographic data, POI data, internet AI data, and statistical yearbook data. Secondly, acknowledging the influence of county-level effects on small towns, we employ the entropy weight-grey correlation model. This model calculates the county-level effects coefficients on small towns and adjusts the small towns index data to incorporate this county-level information. Lastly, we conduct a systematic analysis of the sustainable development levels and obstacles in these towns using a comprehensive evaluation model based on the Principal Component Analysis and Catastrophe Progression Method (PCA-CPM Model).

2.3. Theoretical framework

2.3.1. Sustainable development theory

The theory of sustainable development began with the World Commission on Environment and Development (WCED) in their report "Our Common Future", which defined it as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs," categorizing it into three main dimensions: economic, social, and environmental (Brundtland, 1987). Subsequently, scholars have continually enriched and refined its connotations from these three dimensions (Robert et al., 2005; Kaimuldinova et al., 2024), gradually forming the framework of sustainable development theory. However, in specific fields or issues, some institutions or scholars may adjust these dimensions (Sánchez-Carreira and Blanco-Varela, 2023). For instance, in addressing urban sustainability, Almeida et al. (2018) added the political dimension.

The sustainable development of small towns integrates economic, social, and environmental aspects within the framework of sustainable development theory, balancing various forces within the system to promote sustainability (Mainet, 2015; Surekha, 2022). In addition to the three core dimensions of economy, society, and environment, resources, location, and transportation are also crucial factors for the sustainable development of small towns. Studies have shown that small towns with abundant natural resources (Cong et al., 2021; Xiong et al., 2020), cultural resources (Mayer and Lazzeroni, 2022), tourism resources (Han et al., 2022; Kangshu, 2023), and land resources (Yin et al., 2021) have greater development potential and construction space. Additionally, small towns with advantageous geographical locations can access more development opportunities, such as Xiaoshan Airport Town in Hangzhou (Liao and Yi, 2018). Ren et al. (2020), Tripathi and Mitra (2022) noted that the distance from major city centers and transportation accessibility positively influence small town development. However, Demazière et al. (2024) argued that small towns close to major cities might suffer from the "shadow effect", impacting resource allocation and economic performance. Conversely, small towns farther from major cities can maintain their status and sustainability by fostering local town networks and resource specialization (Bański, 2021).

In China, small towns refer to administrative towns under county-level governments, with limited autonomy (Tong et al., 2020; Yin et al., 2021). Small towns closer to county and municipal governments are more likely to receive funding, policy, and resource support due to their close geographical and social ties. Therefore, this study will explore the sustainable development of small towns in China from four dimensions: economy, society, resources and environment, and location and transportation.

2.3.2. The United Nations Sustainable Development Goals (SDGs)

The Sustainable Development Goals (SDGs) are a set of universally applicable and guiding goals and indicators formulated by the United Nations to improve the quality and efficiency of global ecological environments, economic structures, and social systems(Sánchez-Carreira and Blanco-Varela, 2023). This framework includes 17 goals, 169 specific targets, and 232 indicators (Gupta and Vegelin, 2016). It is widely used in various fields of sustainable development and related policy-making, forming the foundation for ensuring global sustainability (Kaimuldinova et al., 2024). For instance, Wang et al. (2024) assessed regional poverty in China based on SDG 1 (End Poverty), and Zakari et al. (2022) measured energy efficiency in 20 Asian and Pacific (AP) countries based on SDG 7 (Sustainable Energy).

The goal related to the sustainable development of small towns is SDG 11, which aims to "make cities and human settlements inclusive, safe, resilient, and sustainable" (Almeida et al., 2018; Xu et al., 2019). SDG 11 includes ten specific targets (see Table 1) that address sustainable development issues from the perspective of urban and regional planning. Although SDG 11 provides a global framework of specific goals and indicators, it focuses more on overall trends and macro-level objectives, such as housing quality, public spaces, and living environments (Koch and Krellenberg, 2018).

In practice, significant differences in data collection and management capabilities among countries and regions, as well as the need for complex spatial analysis and data sharing for certain SDG 11 indicators (Musango et al., 2020), necessitate localization adjustments

Table 1
SDG 11 and China's action plan.

SDG 11	China's action plan(SDG 11)
11.1 By 2030, ensure access for all to adequate, safe and affordable housing and basic services and upgrade slums.	Promote the development of public rental housing, including the renovation of shantytowns, urban villages, and dilapidated buildings.
11.2 Provide safe and affordable transportation systems for all, and improve road safety.	Promote the development of sustainable urban transportation systems.
11.3 Strengthen inclusive and sustainable urban development, and enhance participatory, integrated, and sustainable planning and management capacities for human settlements.	Enhance urban planning, construction, and management levels, and improve the social governance system.
11.4 Strive to protect and safeguard the world's cultural and natural heritage	Ensure basic cultural services for the public, meet diverse cultural needs, and enhance the protection of intangible cultural heritage.
11.5 Significantly reduce the number of deaths, affected people, and losses caused by various disasters.	Mitigate disasters scientifically according to laws and regulations, focusing on protecting vulnerable groups. Reduce deaths, affected individuals, and economic losses caused by floods significantly.
11.6 Reduce the per capita negative environmental impact of cities.	Promote urban and rural greening by continuously increasing per capita park green space. Enhance urban waste management and advance rural waste management.
11.7 Provide universally safe, inclusive, accessible, and green public spaces for all.	Protect green ecological spaces in urban and rural areas, and promote the construction of green belts and ecological corridors.
11.a Strengthen national and regional development planning to support the establishment of positive economic, social, and environmental links between urban, suburban, and rural areas.	Promote the balanced allocation of public resources between urban and rural areas. Integrate the planning of urban and rural infrastructure networks, extend urban public services to rural areas, and gradually unify the standards and systems of basic public services.
11.b Significantly increase the number of cities and settlements that adopt and implement comprehensive policies for disaster resilience, and establish disaster risk management at all levels.	Promote balanced allocation of public resources between urban and rural areas. Integrate urban and rural infrastructure planning, extend urban public services to rural areas, and gradually unify the standards and systems of basic public services across both areas.
11.c Provide financial and technical assistance to the least developed countries to construct sustainable and disaster-resilient buildings using local materials.	Support the least developed countries in building sustainable infrastructure, promote technical cooperation in energy-efficient construction, and assist in training local skilled workers.

Source:"China's National Plan on Implementation of the 2030 Agenda for Sustainable Development(2016)".

(Hassanzadehkermanshahi and Shirowzhan, 2022). For instance, Koch and Ahmad (2018) analyzed the applicability and data availability of SDG 11 indicators across different countries. They found that India's data availability for many indicators is low, with significant deficiencies in data collection and reporting, while Germany's data availability is higher but still insufficient for certain indicators. Based on these findings, they proposed implementation recommendations tailored to local data sources and city characteristics.

Therefore, developing an indicator system tailored to national conditions is a key challenge in implementing SDG 11. The "China National Plan for Implementing the 2030 Agenda for Sustainable Development" lists actions for implementing the SDGs in China (see Table 1), providing important insights and directions for constructing a theoretical framework for the sustainable development of small towns in China.

2.3.3. Theoretical framework of sustainable development of small towns

Based on the sustainable development theory, UN SDG 11, and China's implementation actions, and considering that counties play a more significant role in the sustainable development of small towns compared to larger cities or provincial regions (Tong et al., 2020, 2021), county-level effects are evident in two main aspects. Firstly, as the basic administrative units under county jurisdiction, county-level policies directly influence various dimensions of sustainable development in small towns. Secondly, in urban planning and urban-rural integration, counties channel high-quality resources to small towns and rural areas, radiating and facilitating the coordinated development of surrounding small towns. In summary, we propose a theoretical framework for the sustainable development of small towns in China, as shown in Fig. 1.

(1) Economy. The economic dimension of sustainable development in small towns is crucial for demonstrating their vitality and potential, encompassing enterprise development and economic service level. Regarding enterprise development, township enterprises have emerged as the main drivers of economic growth in small towns (Han et al., 2021). In other words, towns with a higher number of enterprises indicate higher economic activity rates, industrial agglomeration, and development potential (Senetra and Szarek-Iwaniuk, 2020; Wu et al., 2018). Additionally, the close-knit community relationships in small towns help form robust and reciprocal enterprise innovation ecosystems, fostering unique innovation cultures and activities (Mayer and Lazzeroni, 2022; White, 2022). The congregation of these enterprises has further bolstered and enhanced the economic functions of small towns, becoming vital growth poles for the town's economic scale. Concurrently, as trade and service centers for rural areas, small towns must provide convenient and high-quality diverse services to local resident, as well as excellent financial and commercial services for enterprise transactions (Yu et al., 2023; Surekha, 2022), to reflect the quality of their economic development.
(2) Society. Society is identified as a key target for the sustainable development of small towns, particularly in terms of human-centered social dimensions. This aspect, emphasizing human development and welfare, is deemed essentially crucial for such development (Hu et al., 2022). It encompasses three facets: population, quality of life, and public administration. First, population acts as the foundation of sustainable development in small towns, and the issues of population decline and hollowing out have become notably severe real-world challenges (Liu and Xu, 2021; Steinführer and Grossmann, 2021). Second, the residents are demonstrating growing needs for superior life aspects like leisure, medical care, and technology, and they are demanding higher standards in living environments and quality of life (Jain and Korzhenevych, 2019; Li et al., 2023; Tripathi, 2021). Finally, the enhancement of public management capacities, such as public facilities services and governmental governance, plays a pivotal role in uplifting the social development of small towns (Tripathi and Mitra, 2022).
(3) Resources and Environment. Resources and the environment act as the engine driving the sustainable development of small towns. The distinctive resource endowments and the natural environment provide not only a material basis for this development but also play a pivotal role in shaping their unique advantageous features (Wang et al., 2019). Typically, the area of administrative divisions, diverse land structure uses, scenic spots, and other resource endowments offer advantageous resources and a material base for the sustainable development of small towns (Zhang et al., 2019; Goussous, 2022; Marot and Harfst, 2021). Meanwhile, natural geographical conditions like pronounced topographic undulations and high elevation restrict the development of small towns to a certain degree (Ruban et al., 2021).

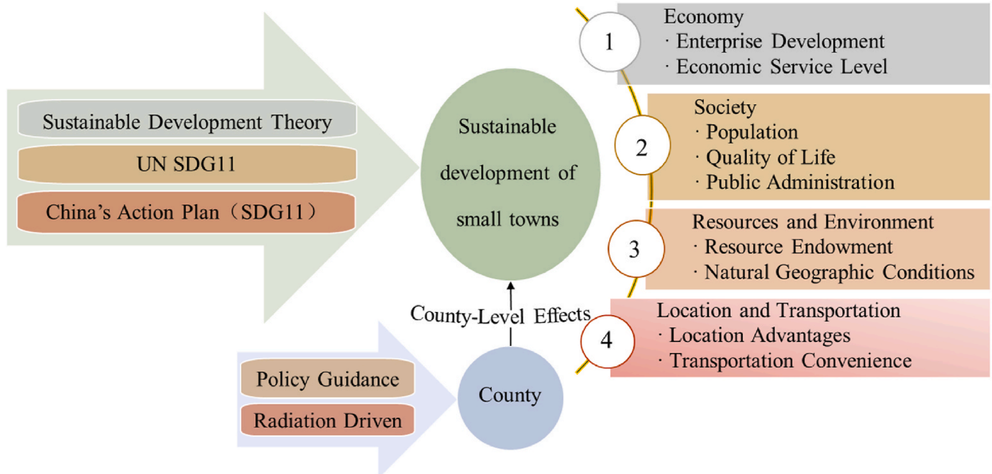

Fig. 1. Theoretical framework of sustainable development in small towns in China.

(4) Location and Transportation. Location and transportation serve as critical bridges in the sustainable development of small towns, acting as vital connectors that facilitate access, communication, and economic interactions. Regarding locational advantages, the small towns that are situated closer to metropolitan circles and urban agglomerations tend to acquire more development resources and potential opportunities from regional integration and development (Zhang et al., 2023; Senetra and Szarek-Iwaniuk, 2020; Scoones and Murimbarimba, 2021). Concurrently, accessible transportation enhances the efficient circulation of several elements like talent, resources, and technology across regions. For instance, high-speed railways can efficaciously lure enterprises, talent settlement, and industrial investments, potentially altering the industrial development configuration of small towns, and even exerting influence on economic structural transition (Chang et al., 2022).

3. Materials and methods

3.1. Study area

The concept of small towns in China differs significantly from other countries (Yin et al., 2021). Most countries define small towns based on population size (Bański, 2021). For example, in Germany, a small town is defined as having 5000 to 20,000 residents (Kuhn, 2015); in Bulgaria, it is defined as a settlement with 10,000 to 30,000 residents (Bański, 2021); and the ESPON TOWN project classifies towns as having approximately 5000 to 50,000 residents (Mayer and Lazzeroni, 2022; Atkinson, 2019). In China, most small towns are defined administratively as "established towns" (Tong et al., 2020; Yin et al., 2021), situated between counties and villages.

The small towns referred to in this study are towns established with the approval of the provincial, autonomous region, and municipality governments, and are grassroots administrative units in China. To assure strictness and typicality in selecting research subjects, towns that are within the top 1000 nationwide in general public budget income, as identified in China County Statistical Yearbook (Township Volume) (2019), are utilized as sample selections. By integrating actual conditions of obtaining multi-source big data and excluding samples with absent data, the final research sample is determined to be 782 small towns. The data samples encompass 25 provinces (areas, cities) and 319 districts and counties (including county-level cities and banners) within China.

3.2. Data sources

Multi-source big data for small towns encompasses remote sensing data, DEM data, great-circle distance data, POI data, internet AI data, statistical yearbooks, and government open data, among others. The details are presented in Table 2.

3.3. Methods

The research design, depicted in Fig. 2, systematically progresses from a theoretical framework to empirical analysis, focusing on sustainable development in small towns. It begins by applying of the theoretical framework proposed in section 2.3.3, and multi-source big data to construct index systems for small towns. We then employ entropy weight-grey correlation analysis to calculate the county-level effects coefficients across various dimensions. These coefficients reflect the extent to which county development impacts small town sustainability and are used to adjust town-level data across different dimensions, thereby integrating these effects into the sustainability profiles of small towns. In the second phase, Principal Component Analysis and the Catastrophe Progression Method are employed to compute a comprehensive sustainable development level. The Natural Breakpoints Method identifies developmental disparities among towns. This analysis covers various dimensions, types, and regions of town development. Finally, an improved obstacle degree model is used to identify factors impeding sustainable development, supported by typical case studies.

3.3.1. The index system of sustainable development of small towns

In section 2.3.3, we proposed a theoretical framework for the sustainable development of small towns. However, selecting specific indicators for each dimension requires further systematic analysis. Therefore, we reviewed relevant scholarly research, summarized the dimensions and corresponding indicators mentioned in these studies, and assessed the contributions and limitations of these indicator systems. The details are shown in Table 3.

From the existing indicator systems, it is evident that the core elements of sustainable development—economic, social, and environmental—are central to these systems. The SDGs provide direction for their construction, while incorporating the characteristics of small towns is crucial for localization. Additionally, considering county-level factors or urban-rural interactions enriches the structural hierarchy of the indicator systems, and utilizing spatial geographic data addresses data scarcity. However, most current indicator systems fail to comprehensively cover the dimensions of economy, society, resources and

Table 2
Multi-source big data for small towns.

Data type	Data description	Data sources
Remote Sensing Data	Land use structure diversity: Classification and statistical analysis of primary land-use types are conducted based on the LUCC (Land Use and Land Cover Change) classification system, adhering to administrative divisions. Calculations are then performed using the land use diversity formula (Velázquez et al., 2018).	Interpretation of remote sensing monitoring data at a 30m spatial resolution, 2020
DEM Data	① Terrain undulation: Derived from the difference between the highest and lowest elevations within the DEM grid of the administrative region. ②Elevation: DEM data is extracted utilizing the geographical coordinates (latitude and longitude) of the townships.	Digital elevation model with 30m spatial resolution 2020, https://www.gebco.net/data_and_products/historical_data_sets/#gebco_2020
Great-circle distance Data	Including the distance from the town government to the county government (in meters) and the distance from the town government to the city government (in meters)	Derived by calculating the latitude and longitude coordinates.
POI and Internet AI Data	It includes POI data and internet AI data. This data originates from electronic maps, O2O type websites, Weibo, and web media publishing sites, and is standardized through processes like web crawling, cleaning, AI algorithm-based categorization, incremental calculation, statistical summarization, and indicator synthesis. Among them, POI includes 16 major categories: companies and enterprises, financial-related services, business residences, transportation facility-related services, road auxiliary facilities, scenic spots, automotive-related services, catering-related services, shopping-related services, lifestyle-related services, sports and leisure-related services, medical and healthcare-related services, accommodation-related services, science and culture-related services, government institutions and social organizations, and public facilities.	Tsinghua DAAS Database 2021, http://www.2861.wiki/#/
Government Open Data	① Statistical Yearbook data. Specifically, population density is calculated based on the registered population and the area of administrative divisions.	China County Statistical Yearbook 2020 (Township Volume), Provincial Statistical Yearbooks 2020, China Urban Statistical Yearbook 2020, https://www.stats.gov.cn/
	② Official open data. Traditional village data is compiled from the first five batches of the list of traditional Chinese villages announced and approved by the Expert Committee for the Protection and Development of Traditional Chinese Villages.	The first to fifth batches of the Directory of Traditional Chinese Villages, http://www.chuantongcunluo.com/index.php/Home/gjml/gjml/wid/2247.html

environment, location and transportation. They also do not align well with the various targets of SDG 11, nor establish the impact relationship between county-level and town-level, or fully leverage the advantages of multi-source big data such as POI, DEM, and internet AI. Therefore, we propose a localized sustainable development indicator system based on sustainable development theory, SDG11,[2] and a comprehensive consideration of the characteristics of Chinese small towns and multi-source big data. The index system that envelops 9 indicators at the criteria layer and 22 indicators at the indicator layer, details of which can be seen in Table 4.

Table 4 shows the specific indicators of each dimension. In the economy dimension, we selected 6 indicators, including the number of industrial enterprises, the number of large-scale industrial enterprises, and financial and insurance-related services, primarily corresponding to SDG 11.a, SDG 11.c, and SDG 11.1, to depict the development of enterprises and the level of economic services in small towns (Shen et al., 2018; Nesticò et al., 2020). In the society dimension, eight indicators such as registered population, convenience-related services, and government organizations and social groups, primarily corresponding to SDG 11.3, SDG 11.6, SDG 11.7, SDG 11.a, and SDG 11.b, outline the basic population status, quality of life of residents, and the level of government public administration in small towns (Stoica et al., 2020). In the dimension of resources and environment, five indicators such as administrative division area, diversity of land use structure, and terrain undulation, are utilized to reflect the resource endowment and natural geographical conditions of small towns (Al-Alawi et al., 2022), primarily corresponding to SDG 11.4 and SDG 11.5. Finally, within the location and transportation dimension, three indicators—distance from the town government to county and city governments, and the transportation facilities and related road infrastructure services—are selected to display the locational advantages and transportation convenience of small towns, primarily corresponding to SDG 11.2.

[2] It is important to note that the Sustainable Development Goals (SDGs) are interrelated (Ohlander et al., 2019). Achieving one goal can be key to addressing others. For instance, SDG 11 reduces urban poverty by providing quality, safe urban housing, thereby supporting SDG 1 "End Poverty." Additionally, by integrating urban planning, affordable housing, pollution reduction, and job creation, SDG 11 supports the achievement of SDG 2 (Food Security), SDG 3 (Promote Health), and SDG 4 (Quality Education) (Sánchez-Carreira and Blanco-Varela, 2023).

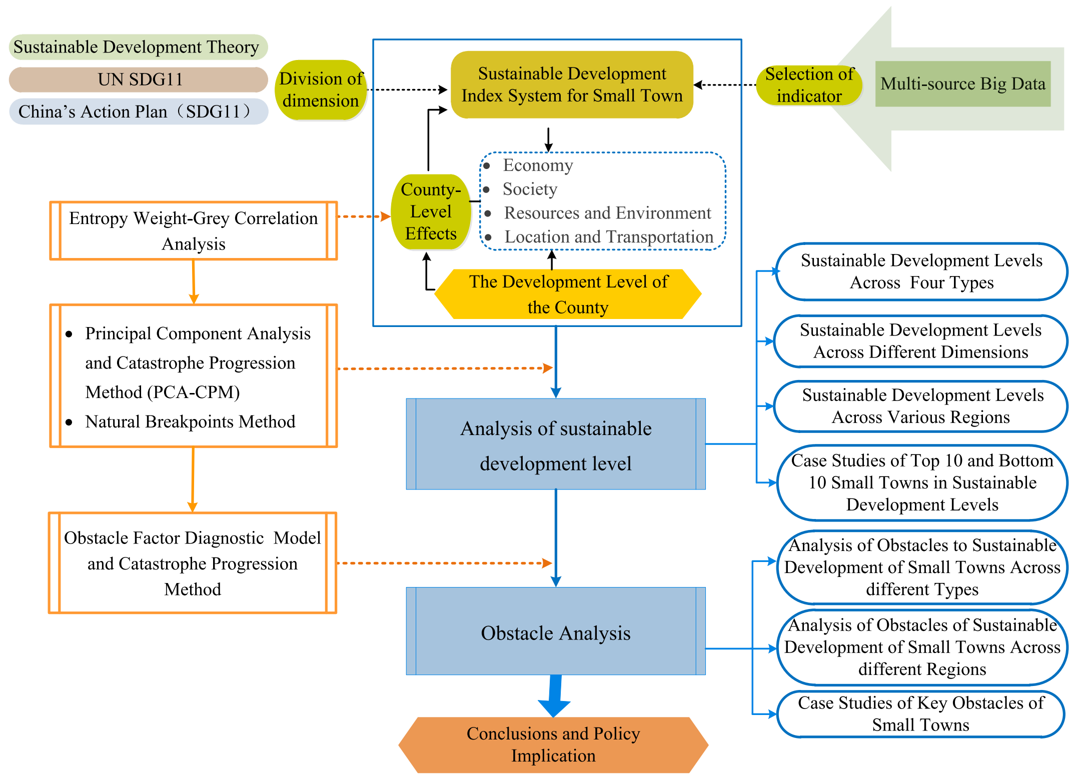

Fig. 2. Key steps in evaluating small town sustainable development.

3.3.2. The county-level effects coefficients based on the entropy weight-grey correlation model

Calculate the county-level effects coefficients that influence various dimensions of sustainable development in small towns. The purpose is to measure the extent of county-level influence on town-level dimensions and, based on this, obtain a town-level dataset incorporating county-level impact factors. The specific steps are as follows.

Step1 Construct a index system to measure county-level effects by referencing the Dimension layer and Criteria layer in the sustainable development index system for small towns. Detailed indicators of each dimension within this system are presented in Table 5.

Compared with the index system for small towns, there are slight differences in the characterization of the economy, resources and environment dimensions, and significant differences in the selection of specific indicators. For example, in the economy dimension, the 'Economic Foundation' primarily represents a county's economic development level, while in the resources and environment dimension, the 'Ecological Environment' underscores the county's environmental development level. The differences between county-level and town-level indicators mainly lie in their focus. County-level effects indicators reflect the development status of various dimensions at the county level, characterized by regional traits, whereas town-level indicators reflect local characteristics (Tong et al., 2020, 2021). Our goal is to infer the impact of county-level development on the sustainable development of small towns by calculating the county's development level across different dimensions. Particularly at the county level, statistical data are more complete, with abundant sources such as Government Open Data and Internet AI data, providing support for more indicators for accurate measurement of county-level effects on small towns across different dimensions.

Step2 To calculate the county-level effects coefficients using the entropy weight-grey correlation model, we consider the complex, ambiguous, and incomplete nature of small town systems. The entropy weight-grey correlation model objectively adjusts the weights of various indicators through a data-driven approach and calculates the grey correlation among different factors (Yang et al., 2023). This model is particularly effective for systems with high multidimensionality, uncertainty, and complexity. For detailed steps on entropy weight calculation and grey correlation analysis, refer to Fu et al. (2021). Using the calculated entropy weights and grey correlation coefficients, the county-level effects coefficients for each criterion layer can be determined. The calculation formula is as follows:

$$R_{ig} = \sum_{j \in g} w_j \xi_i(j) \tag{1}$$

Here, w_j is the entropy weight of indicator j, satisfying $0 \le w_j \le 1$ and $\sum w_j = 1$, $\xi_i(j)$ is the correlation coefficient of indicator j in terms of small town i, and R_{ig} is the county-level effects coefficient of the criteria layer g of the county for on small town i.To obtain a dataset of small towns influenced by county-level effects, multiply these coefficients by the corresponding indicator data of the small towns within the county's jurisdiction.

$$P_{ij} = R_{ig} x_{ij} \tag{2}$$

Let x_{ij} represents the original indicator data of the small town and P_{ij} represents the processed data. The processed data is then normalized.

3.3.3. Sustainable development level of small towns based on PCA-CPM analysis

The catastrophe progression method (CPM) excels in handling complex, multi-layered evaluations, particularly when indicators are conflicting or incompatible (Cheng et al., 2018). It is especially suited for nonlinear systems, effectively managing complex multidimensional data and reducing subjectivity, making it a robust and efficient tool for

Table 3
Contributions and limitations of the existing sustainable development indicator system for small towns.

Theoretical basis	Authors(Year)	Dimensions(Indicators)	Contributions	Limitations
Sustainable Development Theory	Mally et al. (2022)	Economy(4) Society(4) Environment(4)	Follow the three dimensions of sustainable development	Less coverage of indicators
	Hu et al. (2022)	Economic Development (12) Social Development(9) Ecological Development (3)	Construct sub-dimension indicators	Focus on agricultural characteristic towns (AOCTs)
Sustainable Development Goals (SDGs)	Xu et al. (2019)	Housing(1) Traffic(1) Land use and participatory planning(1) Environmental impact(5) Public space(2) Relationship between urban and rural areas(1)	Consider local factors like public space and urban-rural relations	Not aligned with the specific targets of SDG 11
	Ponomareva et al. (2020)	Infrastructure(4) Organisation of waste collection and disposal(2) Population health(2) Education of the population(2) Urban product(2)	Establish an indicator system based on the City Development Index (CDI)	Lacking statistical data support
	Cong et al. (2021)	Natural system(10) Humanity system(9) Residential system(5) Social system(9) Support system(7)	Compare the 17 development goals of the SDGs	Indicators are too scattered
	Hassanzadehkermanshahi and Shirowzhan (2022)	Economic(10) Social Services(13) Environment(10) Health(9) Education (10) Infrastructure(20)	Consider the social services and health indicators	The number of indicators is too many, exceeding over 60
Characteristics of small towns	Xiong et al. (2020)	Scale level(4) Economic development level(8) Social development level (9)	Focus on the scale of small towns, adding relevant indicators such as leisure	Lack environmental dimension
	Nesticò et al. (2020)	Social(24) Economic(42) Environmental(34) Historical-architectural (38)	Introduced the Historical-architectural dimension,and Construct sub-criterion indicators	Only constructed an indicator framework, lacking application
	Li et al. (2023)	Social and economic development(3) Quality of life development(3) Public facilities development(7) Ecological environment development(5)	Introduced dimensions of quality of life and public facility services	More focus on ecological assessment
	Lin et al. (2023)	Economic development(4) Social consciousness(4) Environment sustentation (4) Cultural preservation(4)	Consider cultural, living conditions, and leisure indicators	Lacking statistical data support
Urban-rural interaction	Tong et al. (2021)	Town-level(7) County-level(11)	Consider county-level factor indicators	Not consider the intrinsic connections between county-level and town-level dimensions
	Han et al. (2023)	Rural-urban spatial connection(3) Rural-urban economic ties (4) Rural-urban social integration(4) Rural-urban functional identification(2)	Analyze from the perspective of urban-rural interaction	Some indicators are inherently difficult to represent the urban-rural connection
	Yu et al. (2023)	Natural environment(3) Regional environment(8) Local environment(8)	Consider the overall impact of the region	Overconcentration on environmental indicators
Spatial geographic data	Senetra and Szarek-Iwaniuk (2020)	Demographic(8) Socio-economic(12) Spatio-functional(9)	Consider population and spatial factors	Lack environmental dimension

(*continued on next page*)

Table 3 (*continued*)

Theoretical basis	Authors(Year)	Dimensions(Indicators)	Contributions	Limitations
	Han et al. (2022)	Industrial development(4) Transport location(4) Social livelihood(5) Resource potential(4)	Consider distance factors and made full use of ArcGIS density analysis and POI data	Some indicators have overlapping implications

Table 4
Sustainable development index system for small towns based on the framework of SDG 11.

Dimension layer	Criteria layer	Indicator layer	SDG 11	**References**	Data type
Economy	Enterprise Development (ED)	X_1 Industrial enterprises (count)	SDG 11.a	Han et al. (2022)	Statistical Yearbook
		X_2 Industrial enterprises above designated size (count)	SDG 11.a	Han et al. (2022); Li et al. (2023)	
		X_3 Companies (count)	SDG 11.a	Yu et al. (2023); Senetra and Szarek-Iwaniuk (2020); Tong et al. (2021)	POI
	Economic Service Level (ESL)	X_4Financial and insurance-related services (count)	SDG 11.c	Hu et al. (2022); Shen et al. (2018); Bogdański and Janusz (2022)	
		X_5 Commercial residences (count)	SDG 11.1	Atkinson (2019); Bogdański and Janusz (2022)	
		X_6 Accommodation-related services (count)	SDG 11.1	Ponomareva et al. (2020); Senetra and Szarek-Iwaniuk (2020)	
Society	Population(PS)	X_7 Registered population (people)	SDG 11.3	Yu et al. (2023); Ren et al. (2020)	Statistical Yearbook
		X_8 Population density (people/sq km)	SDG 11.3	Mally et al. (2022); Senetra and Szarek-Iwaniuk(2020); Cong et al. (2021)	
	Quality of life(QL)	X_9 Convenience-related services (count)	SDG 11.7	Lin et al. (2023); Bogdański and Janusz (2022)	POI
		X_{10} Sports and leisure-related services (count)	SDG 11.7	Xu et al. (2019); Xiong et al. (2020)	
		X_{11} Healthcare-related services (count)	SDG 11.b	Surekha (2022); Mally et al. (2022); Ponomareva et al. (2020)	
		X_{12} Science and culture-related services (count)	SDG 11.a	Mally et al. (2022); Yu et al. (2023); Cong et al. (2021)	
	Public Administration (PA)	X_{13} Government organizations and social groups (count)	SDG 11.3	Surekha (2022)	
		X_{14} Public facilities (count)	SDG 11.6	Yamasaki and Yamada (2022)	
Resources and Environment	Resource Endowment (RE)	X_{15} Administrative division area (sq km)	SDG 11.4	Nesticò et al.(2020); Xiong et al. (2020)	Statistical Yearbook
		X_{16} Land use structure diversity index	SDG 11.4	Tripathi et al. (2022); Yu et al. (2023)	land-use classification data
		X_{17} Scenic spots (count)	SDG 11.4	Xu et al. (2019); Xiong et al. (2020)	POI
	Natural Geographic Conditions(NGC)	X_{18} Terrain undulation (meters)	SDG 11.5	Yu et al. (2023); Han et al. (2022); Ren et al. (2020); Shen et al. (2018)	DEM
		X_{19} Elevation (meters)	SDG 11.5	Gong et al. (2022)	
Location and Transportation	Location Advantage(LA)	X_{20} Distance from town government to county government (meters)	SDG 11.2	Yu et al. (2023); Han et al. (2023)	Great-circle distance
		X_{21} Distance from town government to city government (meters)	SDG 11.2	Yu et al. (2023); Han et al. (2022)	
	Transportation Convenience(TC)	X_{22} Transportation facilities and related road infrastructure services (count)	SDG 11.2	Senetra and Szarek-Iwaniuk(2020); Nesticò et al. (2020); Ponomareva et al. (2020)	POI

evaluating intricate systems (Xing et al., 2024). Small town development is influenced by various factors leading to characteristics of abruptness, complexity, and unpredictability (Sánchez-Carreira and Blanco-Varela, 2023). Therefore, CPM provides a robust, objective, and comprehensive method for evaluating the sustainable development of small towns. Detailed steps are outlined below.

Step 1 The type of catastrophe system is typically determined by the number of control parameters. When the number of control parameters ranges from 1 to7,[3] the system exhibits different catastrophe forms (Arnold et al., 2013). The seven classic types in catastrophe theory are Fold, Cusp, Swallowtail, Butterfly, Parabolic Umbilici, Hyperbolic Umbilici, and Elliptic Umbilici (Xing et al., 2024). In evaluation systems, the number of control

[3] According to catastrophe theory, when the number of control parameters exceeds seven, the geometric and topological properties of the model become extremely complex, increasing the difficulty of mathematical processing and complicating interpretation and prediction in practical applications (Arnold et al., 2013). To enhance the model's practicality and comprehensibility, catastrophe theory typically limits the number of control parameters to seven or fewer, ensuring a balance between expressive power and simplicity.

Table 5
Detailed indicators of the county-level effects index system.

Dimension layer	Criteria layer	Indicator layer	Data type
Economy	Economic Foundation	Y_1 GDP(10,000 Yuan)	Statistical Yearbook
		Y_2 Added Value of the Primary Industry (10,000 Yuan)	
		Y_3 Added Value of the Secondary Industry (10,000 Yuan)	
		Y_4 Added Value of the Tertiary Industry (10,000 Yuan)	
		Y_5 General Public Budget Income (10,000 Yuan)	
		Y_6 Industrial Enterprises Above Designated Size (count)	
	Economic Service Level	Y_7 Industrial Coordination Index	Internet AI
		Y_8 Business Environment Index	
Society	Population	Y_9 Population Density (people/sq km)	Internet AI
		Y_{10} Labor Force Proportion (%)	Internet AI
		Y_{11} Elderly Population Proportion (%)	
	Quality of life	Y_{12} Rural Resident Family Engel Coefficient	Statistical Yearbook
		Y_{13} Enrollment of Ordinary Primary and Secondary Schools (people)	Internet AI
		Y_{14} Medical and Health Institution Beds (beds)	
		Y_{15} Infrastructure Coordination Index	
	Public Administration	Y_{16}Local Government Public Service Capability Index	
		Y_{17} Public Service Supply Adequacy Index	
		Y_{18} Positive Public Opinion (10,000 person-times)	
Resources and Environment	Resource Endowment	Y_{19} Traditional Villages (count)	Government Open Data
	Ecological Environment	Y_{20} Ratio of Days with Excellent Air Quality(%)	Internet AI
		Y_{21} Environmental Protection Satisfaction Score	
Location and Transportation	Location Advantage	Y_{22} Distance from County Government to City Government (meters)	Great-circle distance
	Transportation Convenience	Y_{23} Rural Highway Accessibility Index	Internet AI
		Y_{24} Road Network Density Index	

Note: Except for indicators Y_{11},Y_{12} and Y_{22} which are negative indicators, all others are positive indicators.

parameters corresponds to the number of indicators (Cheng et al., 2018). Referring to the number of indicators within index system for sustainable development in small towns (Table 4), only four types are relevant: Fold, Cusp, Swallowtail, and Butterfly. The models for each sub system are as follows:

$$\text{Fold model}: f(x) = 1/3x^3 + ax \tag{3}$$

$$\text{Cusp model}: f(x) = 1/4x^4 + ax^2 + bx \tag{4}$$

$$\text{Swallowtail model}: f(x) = 1/5x^5 + 1/3ax^3 + 1/2bx^2 + cx \tag{5}$$

$$\text{Butterfly model}: f(x) = 1/6x^6 + 1/4ax^4 + 1/3bx^3 + 1/2cx^2 + dx \tag{6}$$

$f(x)$ represents the potential function of a state variable x of a system, and the coefficient a、b、c、d for the state variable x indicates the control variable of that state variable.

Step 2 The importance of indicators within the catastrophe system was ranked using a principal component analysis (PCA) to minimize subjective bias (Jing et al., 2022). The process involves several steps: establishing a covariance matrix of the indicators, calculating the eigenvalues and eigenvectors, determining the weights based on the eigenvector corresponding to the maximum eigenvalue, and finally ranking the indicators by their weights.

Step 3 The indicators within the catastrophe system were normalized based on the their importance ranking. The specific normalization formulas for each type of catastrophe system are as follows:

$$\text{Fold model}: x_a = \sqrt{a} \tag{7}$$

$$\text{Cusp model}: x_a = \sqrt{a}, x_b = \sqrt[3]{b} \tag{8}$$

$$\text{Swallowtail model}: x_a = \sqrt{a}, x_b = \sqrt[3]{b}, x_c = \sqrt[4]{c} \tag{9}$$

$$\text{Butterfly model}: x_a = \sqrt{a}, x_b = \sqrt[3]{b}, x_c = \sqrt[4]{c}, x_d = \sqrt[5]{d} \tag{10}$$

Step 4 Calculate the catastrophe values based on the normalized results of each indicator to reflect the sustainable development level of small towns (Jenifer and Jha, 2017). If the indicators have a non-complementary (non-substitutable), the catastrophe value is the minimum of the normalized results. If the indicators are complementary (substitutable), the catastrophe value is the average of the normalized results. The nature of these relationships is determined by calculating the correlation coefficient between the indicators.

Using the sustainable development indicators of small towns and the above steps, the types of catastrophe systems, the relative importance of indicators, and the complementary relationships among subsystems can be determined. The results are shown in Fig. 3.

Additionally, the following pseudocode (see Table 6) for evaluating the sustainable development of small towns is provided to better understand the analysis steps.

3.3.4. *Diagnosing obstacles to the sustainable development of small towns*

Diagnosing obstacles to the sustainable development of small towns is essential for enhancing development quality and promoting sustainable growth(Shen et al., 2018; Aliaskarov et al., 2023). We integrate the obstacle factor diagnostic model with the catastrophe progression method, resulting in an enhanced diagnostic model (Cheng et al., 2018). The implementation steps are as follows.

Step 1 Calculate the deviation degree of the indicator as: $I_{ij} = 1 - d_{ij}$.

Here, I_{ij} stands for the deviation of the j indicator of the i small town, and d_{ij} denotes the normalized score of the j indicator for the i small town.

Step 2 Calculate the catastrophe value of each indicator's deviation using the normalization formula Eqs. (6)–(10) in the catastrophe progression method. This value measures the obstacle degree for indicators at the criteria layer.

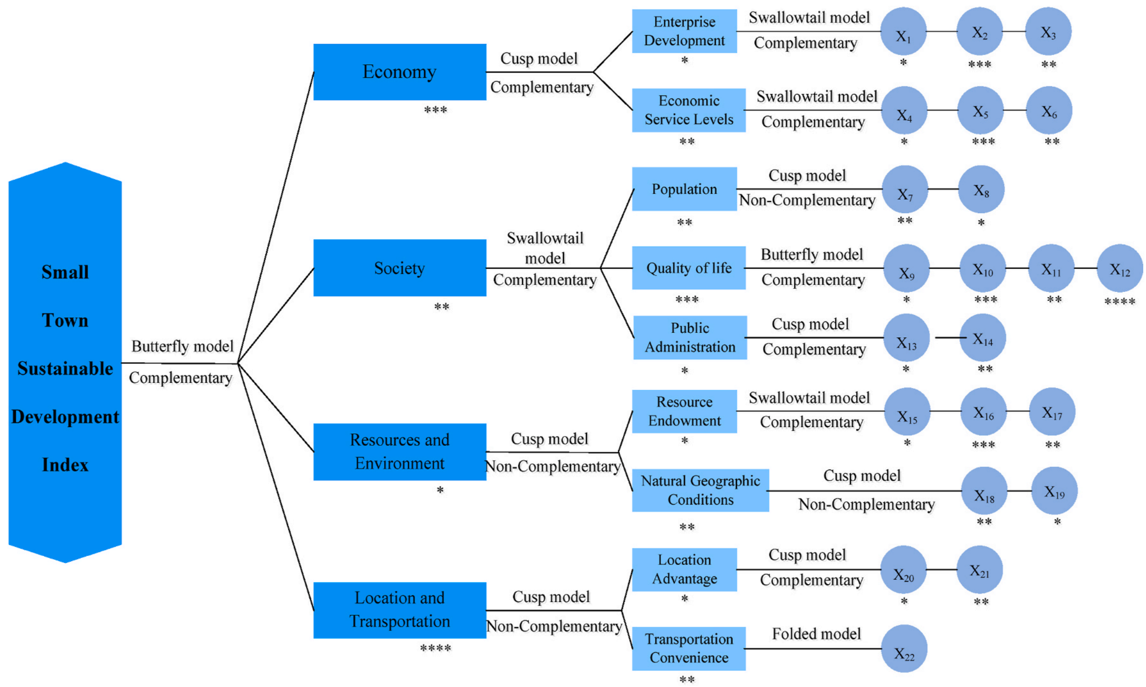

Fig. 3. Types of catastrophes, indicator importance, and complementarity relations in small town sustainable development subsystems.
Note: * denotes the importance ranking of indicators. The greater number of * symbols indicates a higher ranking for the indicator.

Table 6
The algorithm for sustainable development evaluation of small towns using PCA-CPM.

Algorithm: sustainable development evaluation of small towns using PCA-CPM

Input: Country indicator data matrix $H = \left(y_{ij}\right)_{782\times24}$,small town indicator data matrix $X = (x_{ij})_{782\times22}$
Output: Sustainable development levels L_i,sustainable development levels for 4 dimensions and 9 criteria layers L_d and L_c, $i = (1:782)$, $d = (1:4)$, $c = (1:4)$

1 Calculate entropy weights $w(j)$ and grey correlation coefficients $\xi_i(j)$ of each indicator based on the H.
2 Calculate county-level effects coefficients R_{ig} of each criterion layer for $i = 1$ to 782 do Eq. (1)
3 Process small town indicator data using R_{ig} for $i = 1$ to 782 do Eq. (2); then Normalize data $P = (P_{ij})_{782\times22}$.
4 PCA-CPM Analysis for Sustainable Development Level
  Step 1: Determine catastrophe system types and corresponding models for subsystems according the number of indicator of the criteria layer and Eqs. (3)–(6)
  Step 2: Rank indicator importance using PCA
  Step 3: Normalize indicators within each catastrophe system based on the importance ranking and Eqs. (7)–(10), denoted as x_t, where $t \in \{a, b, c, d\}$
  Step 4: Calculate catastrophe values (sustainable development levels in the dimension layer and the criteria layer)
  for each catastrophe system in dimension layer do
    for each catastrophe system in criteria layer do
      if indicators within Indicator layer are complementary then $L_c = \text{mean}(x_t)$
      else $L_c = \min(x_t)$
    if indicators are within the criteria layer complementary then $L_d = \text{mean}(L_c)$
    else $L_d = \min(L_c)$
  Step 5: Obtain Sustainable Development Levels of small towns
    for $i = 1$ to 782 do
      if indicators within the dimension layer are complementary then $L_i = \text{mean}(L_d)$
      else $L_i = \min(L_d)$

Step 3 Determine the obstacle degree of indicators at the dimension layer using this approach, thereby identifying the factors that impact sustainable development within various subsystems of small towns.

4. Results and discussions

4.1. Analysis of sustainable development level

4.1.1. Sustainable development levels across four types

The sustainable development levels of 782 top small towns are classified into four categories: High, Medium-high, Medium-low, and Low, using the Natural Breakpoints Method. Table 7 illustrates the four types of sustainable development of these small towns across China.

Table 7
Four types of 782 top small towns.

Type of small towns	Number	Score range	Mean score	%
High level	191	(0.7841, 1]	0.8345	24.42
Medium-high level	356	(0.6858, 0.7841]	0.7346	45.52
Medium-low level	220	(0.5030, 0.6858]	0.6393	28.13
Low level	15	[0, 0.5030]	0.3867	1.92

Table 7 classifies 782 top small towns into four sustainable development levels based on their scores: Low (score range: [0, 0.5030], 1.92% of towns), Medium-low (score range: (0.5030, 0.6858], 28.13%), Medium-high (score range: (0.6858, 0.7841], 45.52%), and High (score range: (0.7841, 1], 24.42%). The mean scores for these levels are 0.3867

(Low), 0.6393 (Medium-low), 0.7346 (Medium-high), and 0.8345 (High) respectively. Notably, the average score of the High level is about 2.2 times that of the Low level. Furthermore, of the 782 small towns, 412 (52.69%) have scores above the overall average of 0.7255.

Overall, 782 top small towns in China predominantly exhibit a sustainable development level above the medium. There is a relatively small number of towns with lower sustainability levels. This trend suggests that China's small towns have experienced a qualitative improvement in their overall development. The development of small towns has significantly benefited from the Chinese government's rural revitalization strategy (Tong et al., 2020; Yin et al., 2021), urban-rural integration (Han et al., 2023), and characteristic town policies (Zhang et al., 2024; Hu et al., 2022). The "Opinions on Promoting Urbanization with Counties as Important Carriers," released in May 2022, emphasize extending infrastructure and public services from counties to suburban rural areas and larger towns. This policy is crucial for improving the urban system, supporting urban-rural integration, and coordinating urbanization among large, medium, and small cities and towns. These combined policies have facilitated the flow of development factors between urban and rural areas, bolstered economic and industrial growth, alleviated urban-rural imbalances, and enhanced the role of small towns as vital links in urban-rural integration (Ma et al., 2020).

4.1.2. Sustainable development levels across different dimensions

The sustainable development levels of four types of 782 top small towns across different dimensions are illustrated in Fig. 4. Additionally, Table 8 shows the variance and the ratio of the maximum to minimum values for each dimension across the four types of small towns.

Fig. 4 vividly demonstrates that among the 782 top small towns, the almost types achieve the highest scores in the Resources and Environment dimension and the lowest in Location and Transportation. This suggests that resources and environment are key drivers of sustainable development in these small towns, while location and transportation play a less significant role. From the Resources and Environment dimension, most of China's 782 top small towns possess unique geographical features (e.g., Humen Town), natural endowments (e.g., Maotai Town), cultural resources (e.g., Luzhi Town), and tourism resources (e.g., Wuzhen). These irreplaceable resources and environments play a crucial role in enhancing the ecological livability of these small towns (Kangshu, 2023; Yin et al., 2021). Conversely, the Location and Transportation dimension shows less impact on sustainable development, particularly at lower levels. This is primarily due to the fact that transportation infrastructure development in Chinese towns generally lags behind that in major cities, with western regions lagging behind eastern regions, and towns further from major cities lagging behind those closer (Yu et al., 2023), resulting in overall poor performance in location and transportation for Chinese small towns.

Table 8 shows that different types of small towns exhibit unbalanced characteristics across various dimensions. The more balanced the development across dimensions, the higher the level of sustainable development; conversely, imbalanced development leads to poorer outcomes. Numerous studies support this argument. Kaimuldinova et al. (2024), Sánchez-Carreira and Blanco-Varela (2023) argue that the essence of sustainable development lies in achieving stability and balance among economic, social, and ecological dimensions. On the contrary, small towns with imbalanced development face challenges such as economic recession, lagging development, environmental degradation, and shrinkage (Mally et al., 2022; Xiong et al., 2020). Therefore, it is crucial to promote coordinated development across economic, social, resource and environmental, and locational and transportation aspects.

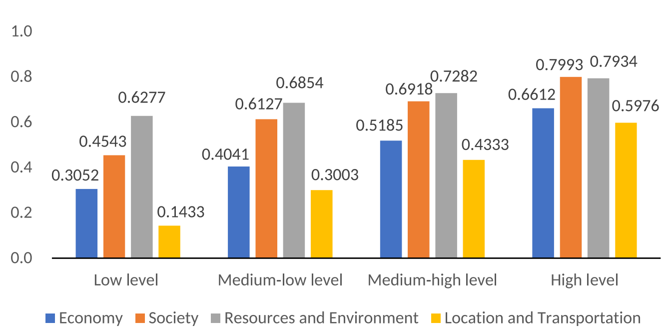

Fig. 4. Sustainable development levels across different dimensions and types in China's 782 top small towns.

Table 8
Variance and ratio across four types of 782 top small towns.

	High level	Medium-high level	Medium-low level	Low level
Var	0.043	0.032	0.020	0.009
max/min	4.38	2.28	1.68	1.32

4.1.3. Sustainable development levels across various regions

The sustainable development levels of 782 top small towns across various regions of China are illustrated in Fig. 5 and Fig. 6.

Figs. 5 and 6 reveal that the sustainable development levels of small towns in China exhibit significant regional and dimensional differences. Similarly, studies by Zhang et al., (2022a)and Sun et al. (2022) on nationwide nighttime lighting and land use data reinforce the presence of these regional differences. Specifically, small towns in the eastern region outperform others in the dimensions of economy, society, location, and transportation, excelling in enterprise development, economic service level, population, quality of life, public management, and transportation convenience (see Fig. 6). For example, towns like Shishan in Guangdong Province and Yushan in Jiangsu Province leverage their coastal locations and transportation advantages to attract numerous enterprises and human resources, significantly boosting economic and public service development (Gong et al., 2022). Conversely, towns in the central, northeastern, and western regions exhibit higher scores in the resources and environmental dimensions compared to those in the eastern regions. For instance, small towns in the western regions possess unique ethnic cultural heritage and abundant natural resources (Xiong et al., 2018), while the central and northeastern regions benefit from flat terrain, fertile land, and rich resources (Liao and Yi, 2018; Hu et al., 2022). Therefore, leveraging these inherent advantages and finding suitable development models are crucial for the sustainable development of small towns.

4.1.4. Case studies of top 10 and bottom 10 small towns in sustainable development levels

A comparative analysis was conducted between the top 10 and bottom 10 of China's top 782 small towns. Table 9 presents the detailed results of this comparison.

From Table 9, we can derive three key conclusions. First, small towns in the eastern region generally rank higher, while those in the western region rank lower. Specifically, the top 10 small towns have average scores of 0.9303, 0.9474, 0.9386, and 0.8480 in the dimensions of economy, society, resources and environment, and location and transportation, respectively. These towns are primarily located in the eastern provinces of Guangdong, Jiangsu, Zhejiang, and Shanghai. In contrast, the bottom 10 small towns have average scores of 0.2061, 0.3637, 0.2355, and 0.0561 in these dimensions, mainly distributed in the central and western provinces of Anhui, Shaanxi, Shanxi, Guangxi, Inner Mongolia, Xinjiang, and Hebei, with a few exceptions in the eastern region. For example, Shishan Town in Guangdong Province excels in all four dimensions, boasting 10,753 industrial enterprises and 1277 large-scale enterprises, forming industrial clusters such as the Nanhai Science and Technology Industrial Park and Changhong Ridge Industrial Park. The town has well-developed infrastructure and ample public services, with significant locational advantages due to major railways like the Guangmao, Guangzhou-Zhuhai, and Guiyang-Guangzhou railways.

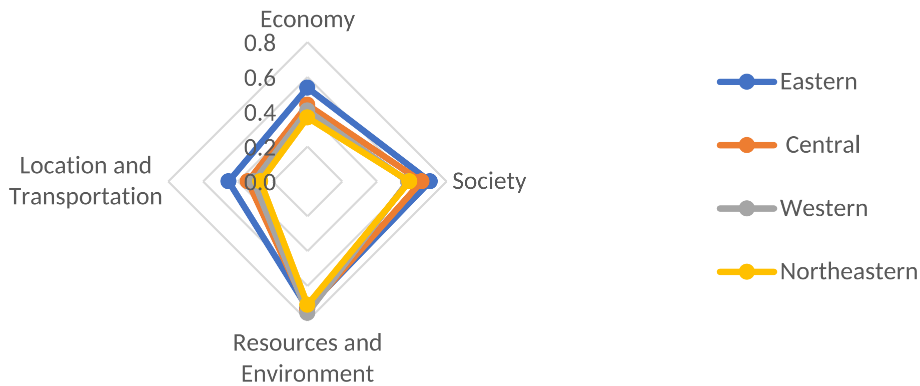

Fig. 5. Sustainable development levels of 782 top small towns across various regions of China in the dimension layer.

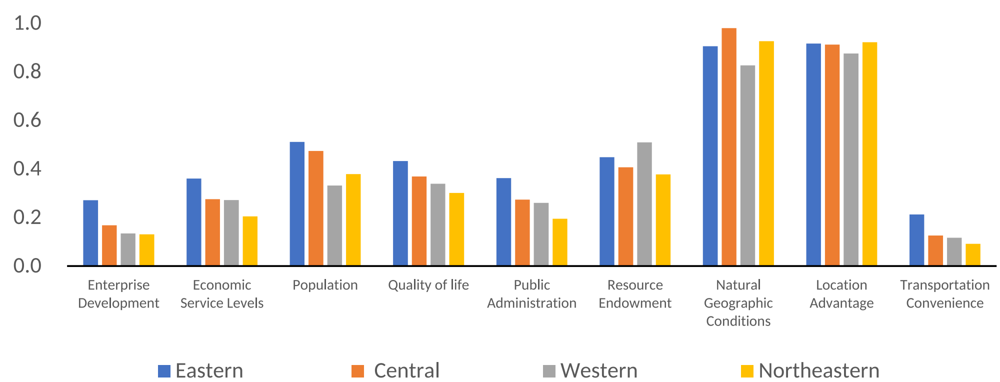

Fig. 6. Sustainable development levels of 782 top small towns across various regions of China in the criteria layer.

Additionally, Shishan Town effectively combines historical and cultural preservation with economic development, implementing the Libian Historical and Cultural Area Protection Plan to maintain the unique value of Libian Ancient Village (Xiang et al., 2020). Conversely, lower-ranking small towns suffer from economic underdevelopment, low population density, limited infrastructure, and inadequate social services. Western small towns face challenges such as complex terrain, ecological sensitivity, underdeveloped transportation infrastructure, and frequent natural disasters (Xiong et al., 2018; Shen et al., 2018). For instance, Dachanghan Town on the Loess Plateau is characterized by hilly and deeply eroded terrain, frequently experiencing natural disasters such as floods, droughts, hail, and frost, presenting extremely harsh locational and transportation conditions.

Secondly, the development dimensions in small towns are interconnected and mutually reinforcing. Specifically, out of the towns that rank in the top 10 for the economy dimension, 8 are also in the top 10 for society, 5 for location and transportation, and 4 for resources and environment. These intrinsic correlations manifest in several ways. On one hand, regional economic development relies on comprehensive infrastructure services, efficient public management, and convenient transportation, which collectively enhance enterprise competitiveness and foster innovation (Senetra and Szarek-Iwaniuk, 2020; Gong et al., 2022; Lin et al., 2023). On the other hand, economic growth generates substantial tax revenue, providing crucial financial backing for improving infrastructure and public social services. This, in turn, attracts high-quality labor and additional social resources (Jin et al., 2022). Evidently, the economy serves as a central driver for both society and advancements in location and transportation (Xiong et al., 2018; Gong et al., 2022), while simultaneously, these two dimensions lay a foundation for further economic growth. Additionally, resources and the environment form the unique advantage and core competitiveness of small towns (Kangshu, 2023).

Lastly, small towns in the more prosperous eastern provinces are often integral parts of city clusters and metropolitan circles. For instance, Yushan Town in Kunshan City, Jiangsu Province, is a pivotal area within the Yangtze River Delta city group, the Shanghai metropolitan region, and the Suzhou-Wuxi-Changzhou urban circle. Under this tight-knit urban cluster, Yushan Town and the Kunshan High-tech Zone implement a unified administrative system, efficiently integrating resources and seamlessly aligning with the rapid regional development, thus leveraging significant developmental momentum and economic spillover benefits. This development model aligns with central place theory and the concept of "borrowing size", wherein small towns can leverage their close ties with counties or larger cities to utilize their resources and opportunities for self-development (Yu et al., 2023; White, 2022; Demazière et al., 2024). In contrast, small towns in economically less developed counties face substantial challenges in economic development. This disparity highlights the importance of harmonizing progress across various dimensions while actively integrating into the cohesive growth of city clusters and metropolitan circles for the sustainable development of small towns.

4.2. Obstacle analysis

4.2.1. Analysis of obstacles to sustainable development of small towns across different types

By employing the obstacle analysis model, the degree of obstacles to sustainable development in 782 top small towns was calculated, and the primary obstacles were identified. The results of different types are presented in Fig. 7 and Fig. 8, respectively.

As depicted in Fig. 7, the economic and social dimensions are the primary obstacles to the sustainable development of small towns. This aligns with the findings of Gong et al. (2022) regarding small towns in Jiangyin City, and Aliaskarov et al. (2023)also noted that economic, social, and ecological factors are common obstacles in the Zhambyl region. Further, as shown in Fig. 8, the key obstacles are enterprise

Table 9
The different dimensions of top 10 and bottom 10 small towns among China's 782 top small towns.

	Economy		Society		Resources and Environment		Location and Transportation	
	Small town	Score	Small town	Score	Small town	Score	Small town	Score
Top 10	Chang'an Town (Dongguan City, Guangdong Province)	1.0000	Dali Town (Nanhai District, Foshan City, Guangdong Province)	1.0000	Shishan Town (Nanhai District, Foshan City, Guangdong Province)	1.0000	Yushan Town (Kunshan, Suzhou, Jiangsu Province)	1.0000
	Humen Town (Dongguan City, Guangdong Province)	0.9582	Yushan Town (Kunshan, Suzhou, Jiangsu Province)	0.9856	Xiqiao Town (Nanhai District, Foshan City, Guangdong Province)	0.9694	Yang She Town (Zhangjiagang City, Suzhou, Jiangsu Province)	0.9193
	Dalang Town (Dongguan City, Guangdong Province)	0.9488	Hutang Town (Wujin District, Changzhou City, Jiangsu Province)	0.9642	Hengdian Town (Dongyang City, Jinhua City, Zhejiang Province)	0.9565	Dali Town (Nanhai District, Foshan City, Guangdong Province)	0.8828
	Tangxia Town (Dongguan City, Guangdong Province)	0.9425	Shishan Town (Nanhai District, Foshan City, Guangdong Province)	0.9514	Lishui Town (Nanhai District, Foshan City, Guangdong Province)	0.9414	Shishan Town (Nanhai District, Foshan City, Guangdong Province)	0.8362
	Shishan Town (Nanhai District, Foshan City, Guangdong Province)	0.9401	Humen Town (Dongguan City, Guangdong Province)	0.9400	Dongqianhu Town (Yinzhou District, Ningbo City, Zhejiang Province)	0.9296	Hutang Town (Wujin District, Changzhou City, Jiangsu Province)	0.8352
	Houjie Town (Dongguan City, Guangdong Province)	0.9254	Chang'an Town (Dongguan City, Guangdong Province)	0.9367	Zhujiajiao Town (Qingpu District, Shanghai)	0.9241	Lecong Town (Shunde District, Foshan City, Guangdong Province)	0.8192
	Liaobu Town (Dongguan City, Guangdong Province)	0.9111	Liaobu Town (Dongguan City, Guangdong Province)	0.9320	Tangxia Town (Rui'an City, Wenzhou City, Zhejiang Province)	0.9199	Humen Town (Dongguan City, Guangdong Province)	0.8152
	Changping Town (Dongguan City, Guangdong Province)	0.9073	Houjie Town (Dongguan City, Guangdong Province)	0.9280	Houjie Town (Dongguan City, Guangdong Province)	0.9178	Chang'an Town (Dongguan City, Guangdong Province)	0.7956
	Dali Town (Nanhai District, Foshan City, Guangdong Province)	0.9070	Yang She Town (Zhangjiagang City, Suzhou, Jiangsu Province)	0.9219	Mudou Town (Wuzhong District, Suzhou, Jiangsu Province)	0.9162	Daba Town (Baoshan District, Shanghai)	0.7897
	Yushan Town (Kunshan, Suzhou, Jiangsu Province)	0.8626	Dalang Town (Dongguan City, Guangdong Province)	0.9143	Dalang Town (Dongguan City, Guangdong Province)	0.9110	Mudou Town (Wuzhong District, Suzhou, Jiangsu Province)	0.7871
Mean		0.9303		0.9474		0.9386		0.8480
Bottom 10	Wanqingsha Town (Nansha District, Guangzhou City, Guangdong Province)	0.2712	Guchengzi Town (Panshan County, Panjin City, Liaoning Province)	0.4840	Yangting Town (Huancui District, Weihai City, Shandong Province)	0.3845	Tuolu Town (Jiangzhou District, Chongzuo City, Guangxi Zhuang Autonomous Region)	0.1267
	Zhao Dianzi Town (Qian'an City, Tangshan City, Hebei Province)	0.2709	Dadukou Town (Dongzhi County, Chizhou City, Anhui Province)	0.4666	Hengqin Town (Xiangzhou District, Zhuhai City, Guangdong Province)	0.3781	Guchengzi Town (Panshan County, Panjin City, Liaoning Province)	0.1189
	Changqing Town (Yushui District, Bengbu City, Anhui Province)	0.2700	Lagumanzu Town (Wanghua District, Fushun City, Liaoning Province)	0.4445	Zhangcun Town (Huancui District, Weihai City, Shandong Province)	0.3551	Lagumanzu Town (Wanghua District, Fushun City, Liaoning Province)	0.1135
	Xinjiang Town (Wongyuan County, Shaoguan City, Guangdong Province)	0.2639	Miaogoumen Town (Fugu County, Yulin City, Shanxi Province)	0.4403	Nanlang Town (Zhongshan City, Guangdong Province)	0.3480	Zhangcunping Town (Yiling District, Yichang City, Hubei Province)	0.1019
	Guchengzi Town (Panshan County, Panjin City, Liaoning Province)	0.2633	Xinmin Town (Fugu County, Yulin City, Shanxi Province)	0.4364	Zhongbei Town (Xiqing District, Tianjin)	0.3266	Yingluo Town (Haicheng City, Anshan City, Liaoning Province)	0.0997
	Lagumanzu Town (Wanghua District, Fushun City, Liaoning Province)	0.2617	Baitang Town (Pinglu District, Shuozhou City, Shanxi Province)	0.4225	Tianmu Town (Beichen District, Tianjin)	0.3205	Miaogoumen Town (Fugu County, Yulin City, Shanxi Province)	0.0000
	Wutubulag Town (Bole City, Xinjiang Uygur Autonomous Region)	0.2422	Laogaochuan Town (Fugu County, Yulin City, Shaanxi Province)	0.3968	Nanding Town (Zhangdian District, Zibo City, Shandong Province)	0.2423	Laogaochuan Town (Fugu County, Yulin City, Shaanxi Province)	0.0000
	Baitang Town (Pinglu District, Shuozhou City, Shanxi Province)	0.1678	Tuolu Town (Jiangzhou District, Chongzuo City, Guangxi Zhuang Autonomous Region)	0.3045	Humen Town (Dongguan City, Guangdong Province)	0.0000	Xinmin Town (Fugu County, Yulin City, Shanxi Province)	0.0000
	Xicun Town (Xiuwu County, Jiaozuo City, Henan Province)	0.0501	Wushenzhao Town (Wushen Banner, Ordos City, Inner Mongolia Autonomous Region)	0.2410	Malu Town (Jiading District, Shanghai)	0.0000	Dachanghan town (Fugu County, Yulin City, Shanxi Province)	0.0000
	Tuolu Town (Jiangzhou District, Chongzuo City, Guangxi Zhuang Autonomous Region)	0.0000	Dachanghan town (Fugu County, Yulin City, Shanxi Province)	0.0000	Haidong Town (Dali City, Yunnan Province)	0.0000	Jinjing Town (Jinjiang City, Quanzhou City, Fujian Province)	0.0000
Mean		0.2061		0.3637		0.2355		0.0561

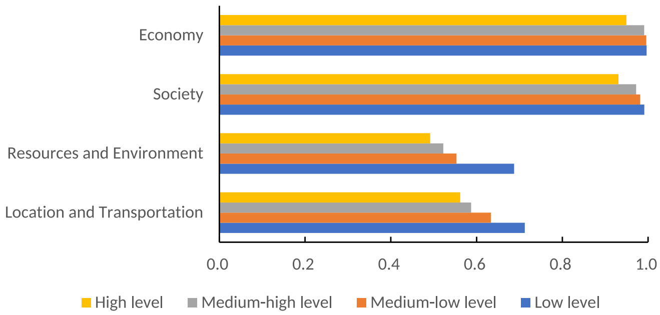

Fig. 7. Obstacle degrees across four types of China's top 782 small towns in different dimensions.

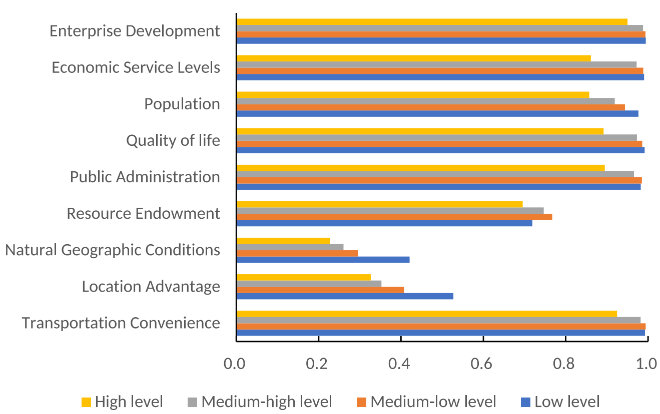

Fig. 8. Obstacle degrees across four types of China's Top 782 small towns in different criteria.

development, economic service level, population, quality of life, public management, and transportation convenience, with average obstacle degrees of 0.9816, 0.9531, 0.9242, 0.9606, 0.9570, and 0.9734, respectively. High-level small towns experience fewer challenges across all dimensions, indicating stronger resilience to various obstacles, while lower-level small towns face more challenges. Despite location advantage and natural geographic conditions having the least impact, with average obstacle degrees of 0.4034 and 0.3012, respectively, lower-level small towns particularly struggle in these areas, highlighting an urgent need to improve transportation infrastructure.

4.2.2. Analysis of obstacles of sustainable development of small towns across different regions

Upon further analyzing the obstacle factors in different regions of the 782 top small towns, the results are displayed in Fig. 9 and Fig. 10.

Across different regions, the economy and society dimensions remain significant obstacles to sustainable development in small towns. As

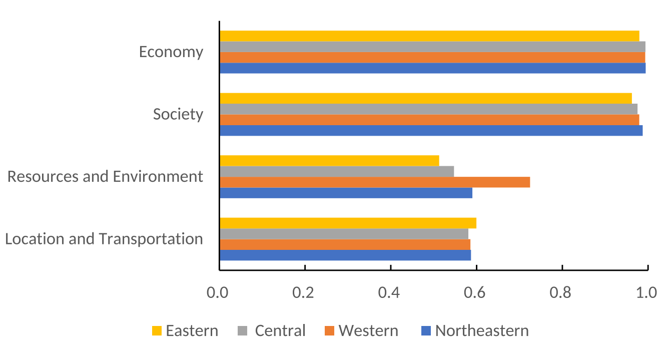

Fig. 9. Obstacle degrees across various regions of China's top 782 small towns in different dimensions.

Fig. 10. Obstacle degrees across various regions of China's 782 top small towns in different criteria.

illustrated in Fig. 10, aside from resource endowment, natural geographical conditions, and location advantage, the degree of other influencing factors as obstacles increases from the east to the northeast. The eastern region faces the least obstacles, while the northeast faces the most. Eastern regions like Zhejiang and Jiangsu have high economic development levels and well-established industrial structures, providing strong risk resilience (Liao and Yi, 2018). In contrast, small towns in the northeast are typically resource-dependent and struggle with issues such as overexploitation of resources and a national economic shift towards the south, leading to economic downturn and population decline (Tong et al., 2020, 2021). Furthermore, resource endowment is a significant obstacle for regions other than the west, primarily due to the rapid diminishment of useable land (Sun et al., 2022). Small towns in the western region, particularly those on the periphery, face development challenges due to factors such as inadequate location and transportation infrastructure, limited openness, and suboptimal economic service levels (Xiong et al., 2018).

4.2.3. Case studies of key obstacles of small towns

To further explore the variations in factors impeding sustainable development across the 782 top small towns, two representative small towns from each of the four types were chosen for detailed analysis. Table 10 presents the obstacle degrees and rankings for various factors within the criteria layer of these selected towns.

In high-level small towns, Shilong Town and Zhuanqiao Town face significant challenges primarily due to resource endowment constraints. Both towns, located in the eastern region, have transformed into processing and manufacturing bases for large enterprises. However, as industrialization progresses, the growing scarcity of resources, particularly land, leads to restricted development space and functional limitations (Sun et al., 2022). In medium-high and medium-low level small towns, such as Tongcheng Town, Caojing Town, Xinjiang Town, and Dewo Town, the primary obstacles are economic service level and quality of life. This indicates a need for improvements in their economic, industrial, and population agglomeration capabilities, as well as in enhancing service levels related to daily life services like dining and shopping, economic services such as finance and insurance, and government management (Yu et al., 2023; Hu et al., 2022). In low-level small towns, such as Tuolu Town and Wushenzhao Town, obstacles include enterprise development, economic service level, quality of life, and public administration. These towns, located in remote areas of the central and western regions, face insufficient industrial support and job opportunities, underdeveloped supporting services, and significant population outflow. Inefficient government management and institutional mechanisms exacerbate these issues, leading to inadequate or inappropriate utilization of their resource endowments (Xiong et al.,

Table 10
Obstacle degrees and rankings for the criteria layers in representative small towns.

Type of small towns	Representative small towns	Degrees(Rankings)								
		ED	ESL	PS	QL	PA	RE	NGC	LA	TC
High level	Shilong Town (Dongguan City, Guangdong Province)	0.9776 (642)	0.9329 (644)	0.6989 (767)	0.9081 (706)	0.9407 (605)	0.8210 (202)	0.1272 (473)	0.3355 (482)	0.9519 (671)
	Zhuanqiao Town (Minhang District, Shanghai)	0.9786 (628)	0.8882 (702)	0.8732 (638)	0.9107 (701)	0.8848 (734)	0.8378 (152)	0.0439 (740)	0.2549 (647)	0.8707 (758)
Medium-high level	Tongcheng Town (Tianchang City, Chuzhou City, Anhui Province)	0.9914 (386)	0.9951 (79)	0.9297 (408)	0.9937 (91)	0.9922 (76)	0.8887 (37)	0.1049 (514)	0.5766 (26)	0.9873 (349)
	Caojing Town (Jinshan District, Shanghai)	0.9943 (275)	0.9911 (164)	0.9713 (80)	0.9938 (89)	0.9833 (204)	0.8168 (217)	0.0715 (638)	0.3826 (354)	0.9795 (486)
Medium-low	Xinjiang Town (Weng Yuan County, Shaoguan City, Guangdong Province)	0.9998 (4)	0.9983 (13)	0.9586 (175)	0.9970 (25)	0.9953 (33)	0.8352 (156)	0.6335 (19)	0.4905 (96)	0.9994 (24)
	Dewo Town (Anlong County, Qianxinan Buyi Miao Autonomous Prefecture, Guizhou Province)	0.9995 (12)	0.9985 (11)	0.9674 (110)	0.9961 (41)	0.9968 (16)	0.7434 (422)	0.6513 (15)	0.4150 (264)	0.9991 (34)
Low level	Tuolu Town (Jiangzhou District, Chongzuo City, Guangxi Zhuang Autonomous Region)	0.9999 (2)	1.0000 (1)	0.9439 (289)	1.0000 (1)	0.9986 (6)	0.6273 (666)	0.5897 (40)	0.5760 (27)	0.9999 (9)
	Wushenzhao Town (Wushen Banner, Ordos City, Inner Mongolia Autonomous Region)	0.9995 (8)	0.9982 (15)	0.9970 (3)	0.9987 (10)	0.9958 (30)	0.1467 (781)	0.2184 (379)	0.6307 (12)	0.9998 (15)

Note: The abbreviations ED, ESL, PS, QL, PA, RE, NGC, LA, and TC stand for different criteria. Enterprise Development (ED); Economic Service Level (ESL); Population (PS); Quality of life (QL); Public Administration (PA); Resource Endowment (RE); Natural Geographic Conditions (NGC); Location Advantage(LA); Transportation Convenience (TC).

2018). Therefore, these towns should capitalize on their local resources, transform their comparative resource advantages into competitive strengths for economic development, and pursue diverse sustainable development strategies (Liao and Yi, 2018).

5. Conclusions and policy implication

This study, based on sustainable development theories, the UN SDG11 framework, and multi-source big data, constructs a sustainable development evaluation index system for small towns in China, encompassing four dimensions—economy, society, resources and environment, and location and transportation—along with 9 criteria and 22 specific indicators. Using the PCA-CPM method, we perform an in-depth analysis of the sustainable development levels and associated obstacles in China's 782 top small towns. The study's primary theory contributions are as follows:

First, it enriches the theoretical framework of sustainable development by integrating the classical dimensions of economy, society, resources and environment, and introducing a new dimension of location and transportation. This better constructs an evaluation index system for sustainable development of small towns tailored to China's context, advancing the implementation of sustainable cities and communities within the SDG11 framework.

Second, by utilizing multi-source big data, including statistical yearbooks, POI data, geospatial data, and AI internet data, we overcome the challenges of traditional data acquisition, improving the quantity and variety of research data on small towns and exploring the practical application of multi-source big data.

Third, by considering and calculating the county-level effects on various dimensions of small town sustainability, we construct a sustainable development evaluation model suited for the complex, multi-layered, and nonlinear characteristics of small towns. The PCA-CPM method systematically evaluates the sustainability of China's 782 top small towns and identifies the key obstacles, achieving a comprehensive and multidimensional quantitative study.

The systematic analysis of the study has led to several significant findings and their policy implications:

Firstly, the average sustainable development score of China's 782 top small towns is 0.7255, with 52.69% scoring above this average, indicating a moderately high level of sustainable development. This underscores the effectiveness of China's rural revitalization strategy, urban-rural integration, and emerging urbanization policies in promoting sustainable development in small towns, enhancing the flow of development factors, integrating urban and rural resources, and optimizing rural industrial structures.

Secondly, the development of small towns reveals significant regional and typological differences, with counties profoundly and systematically influencing their sustainable development. This suggests that small towns across different regions in China should actively explore and leverage their unique aspects in terms of regional culture, industrial development, and ecological environment to establish distinct advantages and competitive strengths, which are crucial for sustainable development. Furthermore, it is essential to encourage small towns in central, western, and northeastern China to integrate into urban agglomerations and metropolitan areas through a county-centered development model. This integration not only facilitates the absorption of industrial transfers from the eastern regions but also allows these towns to leverage the spillover effects of central city development.

Lastly, the economy and society emerge as the foremost obstacles hindering sustainable development, with the impact intensifying progressively from the eastern to the central, western, and northeastern regions. Small towns must strive to overcome challenges posed by economic recession and lagging social development by promoting the synergistic development of the economy, society, and environment. Key strategies include shifting the economic growth model, enhancing infrastructure and public services, and improving residents' quality of life. Additionally, strengthening governmental public management and consistently raising economic service standards are crucial for these towns' progression.

In conclusion, this research serves as a preliminary investigation into 782 top towns in China. Given the vast diversity and number of small towns across the country, future studies should aim to employ a more extensive dataset. This approach will better inform new urbanization and rural revitalization strategies. Additionally, conducting detailed case studies on the developmental mechanisms and evolutionary traits of small towns is crucial for gaining a deeper and more comprehensive understanding.

CRediT authorship contribution statement

Mingman Chen: Writing – original draft, Methodology, Conceptualization. **Chen Chen:** Writing – original draft. **Chi Jin:** Writing – review

& editing, Conceptualization. **Bo Li:** Writing – review & editing. **Yingqing Zhang:** Visualization, Software, Formal analysis. **Ping Zhu:** Writing – review & editing, Methodology.

Declaration of competing interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

Data availability

Data will be made available on request.

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