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## Article

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**Dynamic Balance Evaluation of Urban Public Safety and Smart Sustainable Development**  
**—Based on the Entropy Three Parallel Two-Stage Dynamic DDF Model**

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**Abstract:** Amid the global drive toward smart sustainable urban transformation, public safety is often treated as a secondary concern. As compound risks continue to intensify and overlap worldwide, the dynamic balance between public safety and smart sustainable development warrants systematic evaluation. This study employs the Entropy Three-Parallel Two-stage Dynamic DDF model to measure the dynamic balance level between public safety governance and smart sustainable development across Chinese cities and to identify the relative strengths and weaknesses of different public safety dimensions in the development of smart sustainable cities. The results show that (1) overall, Chinese cities have not yet achieved a dynamic balance between public safety governance and smart sustainable development. Regions with median efficiency or low efficiency are spatially clustered, whereas regions with high efficiency are relatively dispersed. (2) Food safety is the principal bottleneck constraining improvements in smart sustainable development. Infrastructure safety has yet to provide adequate support, the contribution of water safety exhibits a threshold pattern, and the public safety dimensions display a degree of substitutability. (3) Over the sample period, the dynamic balance level first increased and then declined, with a turning point around 2021. Public safety governance and smart sustainable development generally fluctuated in opposite directions. Finally, the study proposes establishing a full-cycle governance system that coordinates safety and development, extending public safety governance from risk prevention to development enablement, and targeting policy measures to specific weaknesses in public safety governance.

**Keywords:** public safety; smart sustainable cities; infrastructure safety; water safety; food safety

## 1. Introduction

Building smart sustainable cities has become a dominant paradigm of urban development worldwide. By deeply integrating the Internet of Things (IoT), big data, artificial intelligence, and green technologies, cities are expected to achieve coordinated improvements in operational efficiency, ecological and low-carbon performance, and residents' well-being (Bibri et al., 2023). Yet, amid the pursuit of smart-city metrics and carbon-neutrality targets, urban public safety is often treated as a secondary concern. In July 2021, a catastrophic rainstorm in Zhengzhou, Henan Province, China, caused widespread power and telecommunications outages. Mobile payments stopped working, shared bicycles could not be unlocked, and food-delivery and ride-hailing platforms became unavailable. The event exposed the vulnerability of smart applications that ordinarily make urban life more convenient.<sup>①</sup> At the same time, data centers are critical infrastructure for smart cities, and their servers depend heavily on cooling systems that consume substantial water resources (Google, 2024). During Europe's extreme heat wave in 2022, a cooling-system failure caused a service outage at Google Cloud's London data center.<sup>②</sup> The incident highlighted digital infrastructure's heavy dependence on reliable cooling and water supplies under extreme climatic conditions. Similarly, in March 2011, the Great East Japan Earthquake destroyed the Fukushima Daiichi Nuclear Power Station and triggered a radioactive-leakage crisis. After the accident, milk and spinach sampled within 30–100 km of the plant were found to exceed safety limits for radioactivity.<sup>③</sup> The annual value of coastal fishery production in Fukushima remains below 40% of its pre-disaster level. Even products that pass safety inspections continue to face strong consumer skepticism; labels identifying Fukushima as the place of origin have become liabilities, and rebuilding trust has been extremely slow and difficult.<sup>④</sup> Nuclear power, originally intended to deliver greener and more efficient energy, can, Once an accident occurs, it inflicts longer-lasting

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① People's Daily Online. (2021, August 2). Reflections on digital cities after the heavy rain in Zhengzhou. <https://house.people.com.cn/n1/2021/0802/c164220-32177864.html>

② Reuters. (2022, July 19). Google Cloud data center in London faces outage on UK's hottest day. Reuters. <https://www.reuters.com/technology/google-cloud-data-center-london-faces-outage-uks-hottest-day-2022-07-19/>

③ The National News. (2011, March 19). Race to cool damaged Japanese reactor as farms report contamination. <https://www.thenationalnews.com/world/asia/race-to-cool-damaged-japanese-reactor-as-farms-report-contamination-1.423912>

④ McNeill, D. (2023, March 13). Japan letter: Twelve years on from Fukushima's horror, fishermen still feel the effects. *The Irish Times*. <https://www.irishtimes.com/world/asia-pacific/2023/03/13/japan-letter-twelve-years-on-from-fukushimas-horror-fishermen-still-feel-the-effects/>

damage on food and water safety than anticipated. Conventional public safety domains such as infrastructure safety, water safety, and food safety are the non-negotiable foundations on which smart sustainable cities depend. If these foundations fail, gains in smartness and sustainability can rapidly unravel.

Although scholars have begun to examine the intersection between smart cities and safety (Laufs et al., 2020), much of the literature focuses on emerging risks such as cybersecurity and data privacy. Systemic risks in conventional domains, including water safety, food safety, and infrastructure safety, remain insufficiently integrated into the smart sustainable city framework. In fact, conventional public safety risks have not disappeared in smart sustainable cities; instead, dense interconnections and real-time dependencies may amplify them dramatically. Cities can be described as amplification systems characterized by positive-feedback mechanisms that continuously magnify inputs. The rise of urban civilization has benefited from cities' amplification of beneficial inputs such as knowledge, safety, and wealth. However, cities also have considerable capacity to amplify harmful inputs. Poverty, crime, traffic congestion, pollution, and epidemics may spread and intensify rapidly in urban settings. When positive feedback from these harmful inputs continues to accumulate, escalate, and ultimately exceeds the system's capacity for control, the result may evolve into an urban disaster (Noennig & Schmiedgen, 2014). Moreover, smart cities exhibit deeper cross-sectoral and cross-domain integration, interconnecting electricity, transportation, communications, energy, and other systems through data sharing and coordinated control (Abbas et al., 2025). Because these systems have long evolved independently along their own trajectories, complete coordination among them is difficult. They therefore generate large volumes of fragmented and heterogeneous information that other systems cannot interpret effectively, namely "noise" (Noennig & Schmiedgen, 2014). In a highly coupled smart city, these initially small, localized disturbances can continually propagate between systems through complex dependencies. The urban "amplifier" mechanism can then amplify "small noise" into "large noise." Once the spread of noise exceeds the system's regulatory capacity, it may trigger cascade effects and feedback effects, causing local anomalies to develop rapidly into large-scale urban disasters. Thus, although smart cities improve system integration and operational efficiency, their highly interdependent structure also makes them more vulnerable and more disaster-prone.

Sustainable Development Goal 11 (SDG 11) of the United Nations *2030 Agenda for*

*Sustainable Development* calls for cities and human settlements to be “inclusive, safe, resilient and sustainable” (United Nations, n.d.). This commitment underscores the need to incorporate the principle that safety is a non-negotiable baseline into frameworks for smart sustainable cities. A relatively mature theoretical framework has emerged for integrating smartness, sustainability, and safety into urban planning. In 2025, the United Nations Human Settlements Programme (UN-Habitat) issued the *International Guidelines on People-Centred Smart Cities*. The guidelines revise earlier technocentric approaches by emphasizing human well-being, safety, and inclusive development and by incorporating data governance, privacy protection, cybersecurity, and urban resilience into urban digital transformation (UN-Habitat, 2025). China has similarly made coordinating development and security a key guiding principle for urban digital transformation. National policy calls for digital technologies to enable urban development while systematically strengthening coordinated governance across cybersecurity, data security, infrastructure safety, and public safety (State Council of the People’s Republic of China, 2024).

Although existing research offers conceptual frameworks integrating smartness, sustainability, and safety, it has yet to empirically examine the effects of public safety on the development of smart sustainable cities. Coordinating public safety governance with smart sustainable development requires systems thinking and the pursuit of dynamic balance within the dialectical relationship between development and security (Ni et al., 2022). This balance is not a static equilibrium but a dynamic state that is continually recalibrated as public safety governance and smart sustainable development reinforce and constrain one another (Hettne, 2010). Public safety governance and smart sustainable development should therefore be evaluated within a unified analytical framework. Using the Entropy Three Parallel Two-stage Dynamic DDF model and provincial-level data for China from 2017 to 2023, this study focuses on the co-evolution of urban public safety governance and smart sustainable development. It addresses the following questions:

(1) Based on total efficiency, this study evaluates the dynamic balance level between public safety governance and smart sustainable development. What spatial distribution characterizes the dynamic balance level between public safety governance and smart sustainable development across China during the study period? How does this level evolve over space and time? (2) Focusing on urban residents' basic survival needs, the public safety stage comprises three sub-stages corresponding to three urban "lifeline systems": the infrastructure safety stage, the water safety

stage, and the food safety stage. This design allows us to examine regional heterogeneity across the three safety dimensions. Which safety dimension, when compromised, constitutes the critical bottleneck to smart sustainable development? (3) Based on the stage efficiency values for the public safety stage and the smart sustainable city stage, the study examines the dynamic interaction between urban public safety and smart sustainable development. Which regions neglect safety during smart sustainable transformation and display a “development first, governance later” pattern? Which regions have a sound foundation for safety governance but lag in smartness and sustainable development, leaving their development potential underutilized?

Accordingly, the study offers three potential contributions. (1) It moves beyond the prevailing approach of treating the balance between safety and development as a static outcome. Instead, it conceptualizes this balance as a process of continuous adjustment and dynamic evolution and develops a dynamic balance framework to identify stage-specific characteristics and evolutionary patterns in the interaction between public safety and smart sustainable development. (2) It moves beyond a single-risk perspective by integrating infrastructure safety, water safety, and food safety into a unified public safety evaluation framework anchored in residents' basic survival needs. On this basis, it classifies regions by efficiency performance to identify imbalance patterns and bottlenecks in the coordinated evolution of public safety and smart sustainable development, thereby providing a basis for differentiated governance. (3) It adds the cultural dimension and lifestyle dimension to the evaluation of smart sustainable development. Alongside the economic dimension, social dimension, and environmental dimension, the framework incorporates residents' behavioral practices and value orientations. This extension highlights how culture and lifestyle transitions shape urban sustainability and broadens the evaluative scope of smart sustainable development.

## **2. Literature Review**

### **2.1 Research on Urban Public Safety**

Early research on urban public safety generally examined individual hazards, including floods (Ishiwatari, 2019), earthquakes (Lam & Kuipers, 2019), food safety incidents (Liu et al., 2019), and infrastructure failures (Guidotti et al., 2016). It focused on the mechanisms through which different hazards arise, assessments of their impacts, and emergency response strategies. This research produced relatively well-developed systems for single-hazard risk management (Kuipers et al.,

2018). However, studying hazards in isolation limits understanding of risk interdependencies, coupled transmission pathways, and system-wide governance within urban public safety systems (Mesa-Gómez et al., 2020).

As urban systems have become more complex, overlapping risks from multiple sources, cascading transmission, and increasingly frequent extreme events have emerged as major challenges for urban public safety governance. Research has consequently shifted from single-risk management toward integrated multi-risk governance (Ahamed et al., 2023). Researchers have further introduced urban resilience theory into public safety governance. This theory emphasizes the capacity of urban systems to withstand, absorb, recover from, and adapt to risk shocks (World Bank, 2013). Research on the concept of urban resilience (Meerow et al., 2016), critical infrastructure resilience (Curt & Tacnet, 2018), and adaptive capacity (Sharifi, 2016) has expanded urban safety research from emergency management to full-cycle risk governance. At the same time, the scope of public safety has broadened. Scholars increasingly examine the integrated governance of infrastructure safety, water safety, food safety, public health, and related domains and seek to develop comprehensive urban public safety assessment frameworks (Wang et al., 2023). Technologies such as big data, IoT, and digital twins are increasingly applied to risk monitoring, early warning, and emergency management, facilitating a shift toward more intelligent and fine-grained urban public safety governance (Shah et al., 2019).

## **2.2 Research on Urban Smart Sustainable Development**

Studies on smart cities emerged during the rapid development of information and communication technologies. Early research focused primarily on applying digital technologies to urban governance, public services, transport management and resource allocation (Pereira et al., 2018; Camero & Alba, 2019), with an emphasis on improving urban operational efficiency and governance capacity through digitalization and smart technologies (Bibri & Krogstie, 2017). This strand of research was largely technology-driven and examined how emerging technologies, including the Internet of Things, big data, cloud computing and artificial intelligence, could support the modernization of urban governance (Han & Hawken, 2018).

As implementation advanced, scholars increasingly recognized that smart city development does not necessarily lead to sustainable development (Yigitcanlar et al., 2019). Reliance on technological innovation alone is insufficient to address urban challenges such as resource

constraints, environmental pollution and social inequality (Cai et al., 2023). Smart city research therefore began to converge more closely with the concept of sustainable development, and smart sustainable cities gradually became an important direction in international scholarship (Bibri, 2018). This literature argues that digital technologies should not merely improve urban operational efficiency; they should also support coordinated development across the economic, social, environmental and governance dimensions, thereby advancing smart and sustainable development in tandem (Wang & Zhou, 2022). In research on smart sustainable cities, scholars have developed multidimensional assessment frameworks covering economic vitality, social well-being, the ecological environment, urban governance and digital infrastructure, while continuously refining indicator systems for smart sustainable development (Wey & Peng, 2021). More recently, as the United Nations Sustainable Development Goals (SDGs) and digital-transformation strategies have gained momentum, increasing attention has been directed to the combined contribution of digital technologies to the green and low-carbon transition, the equalization of public services and the modernization of urban governance (Ramaswami et al., 2016).

### **2.3 Research Integrating Urban Safety and Smart Sustainable Development**

As smart-city development has deepened, the research agenda has expanded from digital-infrastructure construction to comprehensive urban governance, making public safety an increasingly important concern in smart-city development (Meijer & Bolívar, 2016). The convergence of safe-city and smart-city approaches has consequently become an important direction in international research. Existing studies generally argue that urban safety is no longer merely an external condition to be secured during smart-city development; it should also constitute an integral component of smart cities (Laufs et al., 2020).

Existing research integrating safe-city and smart-city approaches has mainly proceeded along three lines. First, it emphasizes that public safety should be embedded throughout the planning, construction and governance of smart cities (Westraadt & Calitz, 2020). Second, it explores how digital technologies can empower urban safety governance, with particular attention to the application of the Internet of Things, big data, artificial intelligence and digital twins in risk monitoring, early warning, emergency response and cross-departmental coordination (Meijer & Thaens, 2018). Third, it develops integrated urban-governance frameworks combining safety, resilience and smart governance, thereby promoting a shift from an efficiency-first approach toward

coordinated progress in safety, resilience and sustainability (Ullah et al., 2021; Jiang et al., 2022).

Overall, existing research has advanced the safe city and smart city concepts from relatively separate agendas towards coordinated development and has laid an important foundation for analysing the coordinated development of public safety and smart sustainable development. Nevertheless, several gaps remain. First, existing studies focus more heavily on emerging safety issues such as public order, cybersecurity, data security and privacy protection, while providing limited systematic integration of public-safety concerns directly related to basic human needs, including infrastructure safety, water safety and food safety. A unified analytical framework encompassing multiple dimensions of public safety has yet to be fully established. Second, the literature has mainly examined how digital technologies improve public-safety governance capacity, with less attention to public safety as a foundational support for smart sustainable city development and to the bidirectional interactions and mechanisms linking safety and development. Third, most studies rely on static indicator assessments or analyses of individual risks, and relatively few examine, from the perspective of overall urban operation, the dynamic evolution of interactions between public safety subsystems and smart sustainable development.

### **3. Research Methodology**

#### **3.1 The Entropy Method**

Since some input and output indicators are multidimensional, directly incorporating all individual indicators into the DEA model may bias efficiency estimates and weaken the model's discriminatory power. Therefore, following Shannon (1948), the entropy method is employed to objectively weight and aggregate individual indicators within the same dimension, thereby reducing the dimensionality of multidimensional indicators. Specifically, in the public safety stage (S1), the input indicators of the three parallel sub-stages are aggregated separately, while the output indicators are classified into desirable and undesirable outputs and aggregated accordingly. In the smart sustainable development stage (S2), the input and output indicators are aggregated separately across five dimensions: social, economic, environmental, cultural, and lifestyle. If a dimension contains only one individual indicator, the indicator is directly incorporated into the DEA model after standardization. To ensure comparability across years, a common set of indicator weights is calculated using all observations from the 30 provincial-level regions over the 2017–2023 period

and applied consistently throughout the study period. Table 2 presents the detailed individual indicators and their corresponding composite indicators.

Step 1: Data standardization.

The study covers  $T = 7$  periods (2017–2023),  $M = 30$  provincial-level regions, and  $N$  indicators.  $x_{tmn}$  denotes the original value of indicator  $n$  for provincial-level region  $m$  in period  $t$ . Positive and negative indicators are standardized separately according to their directional properties.

For positive indicators:

$$r_{tmn} = \frac{x_{tmn} - \min_{t,m}(x_{tmn})}{\max_{t,m}(x_{tmn}) - \min_{t,m}(x_{tmn})} \quad (1)$$

For negative indicators:

$$r_{tmn} = \frac{\max_{t,m}(x_{tmn}) - x_{tmn}}{\max_{t,m}(x_{tmn}) - \min_{t,m}(x_{tmn})} \quad (2)$$

where  $r_{tmn}$  denotes the standardized value, and  $\max_{t,m}(x_{tmn})$  and  $\min_{t,m}(x_{tmn})$  denote the maximum and minimum values, respectively, of indicator  $n$  across all provincial-level regions and periods

Step 2: Calculate the proportion of each standardized indicator.

$$P_{tmn} = \frac{r_{tmn}}{\sum_{t=1}^T \sum_{m=1}^M r_{tmn}} \quad (3)$$

where  $P_{tmn}$  denotes the proportion of the standardized value of indicator  $n$  for provincial-level region  $m$  in period  $t$  relative to the sum of all provincial-level-region–year standardized values for that indicator.

Step 3: Calculate the entropy value  $e_n$  of indicator  $n$ .

$$e_n = -k \sum_{t=1}^T \sum_{m=1}^M P_{tmn} \ln(P_{tmn}) \quad (4)$$

where

$$k = \frac{1}{\ln(TM)}$$

When  $P_{tmn} = 0$ ,  $P_{tmn} \ln(P_{tmn})$  is defined as zero.

Step 4: Calculate the divergence coefficient  $g_n$  of indicator  $n$ .

$$g_n = 1 - e_n \quad (5)$$

Step 5: Calculate the weight  $w_n$  of indicator  $n$ .

$$w_n = \frac{g_n}{\sum_{n=1}^N g_n} \quad (6)$$

Step 6: Calculate the composite indicator value.

$$S_{tm} = \sum_{n=1}^N w_n r_{tmn} \quad (7)$$

where  $S_{tm}$  denotes the composite indicator value for the corresponding dimension of provincial-level region  $m$  in period  $t$ . The composite indicators for each dimension are calculated accordingly and incorporated into the DEA model as the corresponding inputs, desirable outputs, or undesirable outputs.

### 3.2 Entropy Three Parallel Two-stage Dynamic DDF model

#### 3.2.1 Indicator Selection

To examine the impact of urban public safety on smart sustainable development, this study employs the Entropy Three Parallel Two-stage Dynamic DDF model, with public safety as the first stage (S1) and smart sustainable development as the second stage (S2), to assess the dynamic balance level between urban public safety governance and smart sustainable development.

The public safety stage (S1) comprises three parallel sub-stages: the infrastructure safety sub-stage (S1.1), the water safety sub-stage (S1.2), and the food safety sub-stage (S1.3). The essence of public safety lies in safeguarding residents' basic survival needs and ensuring the continued operation of essential urban functions. From the perspective of urban lifeline systems, infrastructure provides the physical foundation for various urban activities, water resources are indispensable to residents' survival and productive activities, and food supply is closely related to residents' health and social stability. Accordingly, this study measures urban public safety across three dimensions: infrastructure safety, water safety, and food safety.

For the smart sustainable development stage (S2), relevant input and output indicators are selected across five dimensions: social, economic, environmental, cultural, and lifestyle dimensions. Existing sustainability assessment frameworks tend to be biased towards particular dimensions,

focusing either on the environmental dimension or on the social dimension (Albino et al., 2015). Such imbalances, however, may lead to weak sustainability (Berardi, 2013). The sustainable development of smart cities should take into account ecological, economic, and equity considerations. Accordingly, economic, social, and environmental sustainability are selected as the three fundamental dimensions for S2. In addition, given that each city has its own distinctive local culture and traditions, and that culture profoundly influences residents' consumption patterns and lifestyles and plays a key role in urban development, culture is included as the fourth dimension. Meanwhile, existing sustainability assessment frameworks rarely consider lifestyles that promote harmonious coexistence between humans and nature (Albino et al., 2015). As residents are key stakeholders in urban life, evaluation indicators should also reflect residents' lives and experiences from their perspective (Albino et al., 2012). Lifestyle is therefore included as the fifth dimension. The specific definitions of the indicators for each stage and dimension are presented in Table 1.

**Table 1 Definitions of Indicators for the Public Safety and Smart Sustainable Development**

| Stages                                        |                                                                                                                                                                                                                                                                                                                                                        |                                                                        |
|-----------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------|
| Indicator                                     | Definition                                                                                                                                                                                                                                                                                                                                             | References                                                             |
| <b>S1 Public Safety Stage</b>                 |                                                                                                                                                                                                                                                                                                                                                        |                                                                        |
| S1.1 Infrastructure Safety Sub-stage          | Measures the safety level of urban infrastructure systems, focusing on the capacity of infrastructure elements, including road network coverage, public transport capacity, road lighting conditions, and fiscal support for transportation, to support passenger transport safety and accident prevention                                             | Tonn et al., 2020; Paliotto et al., 2024                               |
| S1.2 Water Safety Sub-stage                   | Assesses the safety level of urban water-resource systems based on infrastructure conditions, including drainage networks and water-supply facilities, as well as governance inputs such as wastewater treatment and soil and water conservation, reflecting the effectiveness of sustainable water-resource utilization and environmental protection. | OECD, 2016; Jensen & Wu, 2018                                          |
| S1.3 Food Safety Sub-stage                    | Measures the safety level of urban food-supply systems, considering basic conditions such as agricultural production inputs and material reserves, as well as food-security outcomes including residents' food affordability, food-price accessibility, food-supply adequacy, and child nutrition and health.                                          | FAO, 2013; Manikas et al., 2023                                        |
| <b>S2 Smart Sustainable Development Stage</b> |                                                                                                                                                                                                                                                                                                                                                        |                                                                        |
| Social Dimension                              | Assesses the overall level of urban social sustainability, focusing on public-service inputs such as social security, education, and healthcare, as well as social development outcomes including demographic structure, educational attainment, health, and social welfare.                                                                           | Huovila et al., 2019; Bhattacharya et al., 2020; OECD, 2020; ITU, 2022 |
| Economic Dimension                            | Measures the overall level of urban economic sustainability, focusing on inputs of production factors such as labor, water resources, and energy, as well as high-quality                                                                                                                                                                              |                                                                        |

|                         |                                                                                                                                                                                                                                                                                                                                    |  |
|-------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--|
|                         | economic development outcomes including economic development, industrial-structure optimization, and innovation capacity.                                                                                                                                                                                                          |  |
| Environmental Dimension | Assesses the overall level of urban environmental sustainability, considering fiscal expenditure on environmental protection, as well as environmental performance in industrial pollution control, water-resource and clean-energy utilization, ecological greening, and urban environmental management.                          |  |
| Cultural Dimension      | Assesses the overall level of urban cultural sustainability, focusing on fiscal expenditure on culture, sports, and media, as well as cultural-service provision reflected in the coverage of cultural facilities such as museums, libraries, and cultural centers, performing arts activities, and cultural-industry development. |  |
| Lifestyle Dimension     | Measures the overall level of urban lifestyle sustainability, focusing on public-service inputs for urban and rural community affairs, as well as quality-of-life outcomes related to green mobility, everyday convenience, and leisure and recreation.                                                                            |  |

Furthermore, the stages are connected by links. In this model, the desirable outputs of the infrastructure safety (S1.1), water safety (S1.2), and food safety (S1.3) sub-stages are also treated as intermediate products (Links) and serve as inputs to the smart sustainable development stage (S2). Different study periods are connected by carry-overs, with all input and output variables carried over to the subsequent period,  $t+1$ . In this model, Fixed Asset Investment is specified as the carry-over variable. Based on the above framework, and with reference to the relevant literature and consideration of data availability, the evaluation indicator system shown in Table 2 is constructed.

**Table 2 Input and Output Indicators for Each Stage**

| Stage/<br>Dimension                                      | Input/<br>Output | Entropy<br>Method<br>Applied | Specific Indicator                            | Unit               | Notes                 |
|----------------------------------------------------------|------------------|------------------------------|-----------------------------------------------|--------------------|-----------------------|
| <b>S1 Public Safety Stage</b>                            |                  |                              |                                               |                    |                       |
| <b>S1.1<br/>Infrastructu<br/>re Safety<br/>Sub-stage</b> | Input            | Yes                          | Road Length                                   | 10,000 km          |                       |
|                                                          |                  |                              | Number of Public Transport Vehicles           | vehicles           |                       |
|                                                          |                  |                              | Number of Urban Road Lighting Lamps           | lamps              |                       |
|                                                          |                  |                              | Transportation Expenditure                    | 100 million<br>CNY |                       |
|                                                          | Output           | No                           | Passenger Volume                              | 10,000 persons     |                       |
|                                                          |                  | Yes                          | Total Number of Traffic Accidents             | cases              | Undesirable<br>Output |
|                                                          |                  |                              | Total Number of Deaths in Traffic Accidents   | persons            | Undesirable<br>Output |
|                                                          |                  |                              | Total Number of Injuries in Traffic Accidents | persons            | Undesirable<br>Output |

|                                                                    |        |     |                                                                                         |                    |                    |
|--------------------------------------------------------------------|--------|-----|-----------------------------------------------------------------------------------------|--------------------|--------------------|
|                                                                    |        |     | Total Direct Property Losses from Traffic Accidents                                     | 10,000 CNY         | Undesirable Output |
| Link from S1.1 to S2                                               |        | No  | Passenger Volume                                                                        | 10.000 persons     |                    |
| S1.2<br>Water Safety<br>Sub-stage                                  | Input  | Yes | Length of Urban Drainage Pipelines                                                      | 10,000 km          |                    |
|                                                                    |        |     | Length of Water Supply Pipelines                                                        | km                 |                    |
|                                                                    |        |     | Effective Irrigated Area                                                                | 1,000 ha           |                    |
|                                                                    |        |     | Daily Urban Wastewater Treatment Capacity                                               | 10,000 m³          |                    |
|                                                                    |        |     | Annual Completed Investment in Soil and Water Conservation and Ecological Projects      | 10,000 CNY         |                    |
|                                                                    |        |     | Water Resources per Capita                                                              | m³ /person         |                    |
|                                                                    | Output | No  | Comprehensive Water Supply Capacity                                                     | 10,000 m³ /day     |                    |
|                                                                    |        | Yes | Water Consumption per 10,000 CNY of GDP                                                 | m³ /10,000 CNY     | Undesirable Output |
|                                                                    |        |     | Daily Domestic Water Consumption per Capita                                             | L                  | Undesirable Output |
|                                                                    |        |     | Chemical Oxygen Demand (COD) Emissions                                                  | 10.000 tonnes      | Undesirable Output |
| Ammonia Nitrogen Emissions per 1,000 CNY of Industrial Value Added |        |     | mg/1,000 CNY                                                                            | Undesirable Output |                    |
| Link from S1.2 to S2                                               |        | No  | Comprehensive Water Supply Capacity                                                     | 10,000 m³ /day     |                    |
| S1.3<br>Food Safety<br>Sub-stage                                   | Input  | Yes | Total Power of Agricultural Machinery                                                   | 10,000 kW          |                    |
|                                                                    |        |     | Expenditure on Grain and Edible Oil Reserve Management and Related Affairs              | 100 million CNY    |                    |
|                                                                    | Output | Yes | Share of Per Capita Expenditure on Food, Tobacco and Alcohol in Consumption Expenditure | %                  |                    |
|                                                                    |        |     | Per Capita Disposable Income                                                            | CNY                |                    |
|                                                                    |        |     | Consumer Price Index for Food                                                           | -                  |                    |
|                                                                    |        |     | Grain Output per Capita                                                                 | kg                 |                    |
|                                                                    |        | No  | Proportion of Children Under 5 with Moderate or Severe Malnutrition                     | %                  | Undesirable Output |
| Link from S1.3 to S2                                               |        | Yes | Share of Per Capita Expenditure on Food, Tobacco and Alcohol in Consumption Expenditure | %                  |                    |
|                                                                    |        |     | Per Capita Disposable Income                                                            | CNY                |                    |
|                                                                    |        |     | Consumer Price Index for Food                                                           | -                  |                    |
|                                                                    |        |     | Grain Output per Capita                                                                 | kg                 |                    |
| S2 Smart Sustainable Development Stage                             |        |     |                                                                                         |                    |                    |
| Social Dimension                                                   | Input  | Yes | Social Security and Employment Expenditure                                              | 100 million CNY    |                    |
|                                                                    |        |     | Education Expenditure                                                                   | 100 million CNY    |                    |

|                         |        |     |                                                                                     |                             |                    |
|-------------------------|--------|-----|-------------------------------------------------------------------------------------|-----------------------------|--------------------|
|                         |        |     | Healthcare Expenditure                                                              | 100 million CNY             |                    |
|                         | Output | yes | Population Growth Rate                                                              | %                           |                    |
|                         |        |     | Share of Population Aged 65 and Above                                               | %                           | Undesirable Output |
|                         |        |     | Number of Students Enrolled in Higher Education Institutions per 100,000 Population | persons                     |                    |
|                         |        |     | Primary School Student – Teacher Ratio (Teachers = 1)                               | -                           |                    |
|                         |        |     | Number of Beds in Medical Institutions per 10,000 Population                        | beds                        |                    |
|                         |        |     | Number of Licensed (Assistant) Physicians per 10,000 Population                     | persons                     |                    |
|                         |        |     | Number of Urban Employees Covered by Pension Insurance                              | 10.000 persons              |                    |
|                         |        |     | Minimum Living Allowance Standard for Urban Residents                               | 10.000 CNY/person • day     |                    |
|                         |        |     | Number of Elderly Care Institutions                                                 | institutions                |                    |
| Economic Dimension      | Input  | Yes | Number of Employed Persons                                                          | 10.000 persons              |                    |
|                         |        |     | Total Water Consumption                                                             | 100 million m <sup>3</sup>  |                    |
|                         |        |     | Electricity Consumption                                                             | 100 million kWh             |                    |
|                         | Output | Yes | Gross Regional Product Index                                                        | %                           |                    |
|                         |        |     | Industrial Structure Upgrading (Tertiary Industry Output/Secondary Industry Output) | -                           |                    |
|                         |        |     | Industrial Structure Rationalization (Theil Index)                                  | -                           |                    |
|                         |        |     | Share of Enterprises Engaged in E-commerce Transactions                             | %                           |                    |
|                         |        |     | Total Telecommunications Business Volume per Capita                                 | CNY/person                  |                    |
|                         |        |     | Number of R&D Outputs                                                               | items                       |                    |
|                         |        |     | Full-Time Equivalent of R&D Personnel                                               | person-years                |                    |
| Environmental Dimension | Input  | No  | Environmental Protection Expenditure                                                | 100 million CNY             |                    |
|                         | Output | Yes | Treatment Capacity of Industrial Wastewater Treatment Facilities                    | 10.000 tonnes/day           |                    |
|                         |        |     | Treatment Capacity of Industrial Waste Gas Treatment Facilities                     | 10.000 m <sup>3</sup> /hour |                    |
|                         |        |     | Water Consumption per Capita                                                        | m <sup>3</sup> /person      | Undesirable Output |

|                     |        |     |                                                                 |                            |  |
|---------------------|--------|-----|-----------------------------------------------------------------|----------------------------|--|
|                     |        |     | Total Urban Natural Gas Supply                                  | 100 million m <sub>3</sub> |  |
|                     |        |     | Green Coverage Rate of Built-up Areas                           | %                          |  |
|                     |        |     | Harmless Treatment Capacity of Municipal Solid Waste            | tonnes/day                 |  |
|                     |        |     | Road Cleaning and Maintenance Area                              | 10,000 m <sup>2</sup>      |  |
| Cultural Dimension  | Input  | No  | Culture, Sports & Media Expenditure                             | 100 million CNY            |  |
|                     | Output | Yes | Number of Museums                                               | institutions               |  |
|                     |        |     | Number of Public Libraries                                      | institutions               |  |
|                     |        |     | Number of Cultural Centers (Stations)                           | institutions               |  |
|                     |        |     | Number of Performances and Screenings at Performing Arts Venues | 1,000 performances         |  |
|                     |        |     | Audience Attendance at Performing Arts Venues                   | 1,000 person-times         |  |
|                     |        |     | Value Added of Cultural and Related Industries                  | 100 million CNY            |  |
| Lifestyle Dimension | Input  | No  | Urban & Rural Community Affairs Expenditure                     | 100 million CNY            |  |
|                     | Output | Yes | Number of Public Transport Vehicles per 10,000 Population       | Standard vehicles          |  |
|                     |        |     | Total Length of Public Transport Routes                         | km                         |  |
|                     |        |     | Urban Road Area per Capita                                      | m <sup>2</sup> /person     |  |
|                     |        |     | Number of Domain Names                                          | 10,000                     |  |
|                     |        |     | Public Park Green Space per Capita                              | m <sup>2</sup> /person     |  |
|                     |        |     | Number of Entertainment Venues                                  | establishments             |  |
| Carry-over          |        | No  | Fixed Asset Investment                                          | 100 million CNY            |  |

### 3.2.2 Model Construction: Entropy Three Parallel Two-Stage Dynamic DDF model

Since decision-making units (DMUs) on the efficiency frontier select the most favorable final weighted outputs, the efficiency of each DMU under the common frontier can be obtained through the following linear programming procedure. The equations below are used to calculate the total efficiency, period efficiency, stage efficiency, and stage efficiency in each period for each decision-making unit (DMU)<sub>p</sub>.

Assume that the model covers  $t$  periods ( $t = 1, \dots, T$ ), with  $n$  decision-making units  $DMU_s$  ( $j = 1, \dots, n$ ) in each period. The model consists of two stages: the public safety stage (S1) and the smart sustainable development stage (S2).

The public safety stage (S1) comprises three parallel sub-stages: infrastructure safety (S1.1), water safety (S1.2), and food safety (S1.3). The infrastructure safety sub-stage (S1.1) has A1 inputs,  $IN11_{aj}^t (a1 = 1, \dots, A1)$ ; B1 desirable outputs,  $O11_{bj}^t (b1 = 1, \dots, B1)$ ; and D1 undesirable outputs,  $U11_{dj}^t (d1 = 1, \dots, D1)$ . The water safety sub-stage (S1.2) has A2 inputs,  $IN12_{aj}^t (a2 = 1, \dots, A2)$ ; B2 desirable outputs,  $O12_{bj}^t (b2 = 1, \dots, B2)$ ; and D2 undesirable outputs,  $U12_{dj}^t (d2 = 1, \dots, D2)$ . The food safety sub-stage (S1.3) has A3 inputs,  $IN13_{aj}^t (a3 = 1, \dots, A3)$ ; B3 desirable outputs,  $O13_{bj}^t (b3 = 1, \dots, B3)$ ; and D3 undesirable outputs,  $U13_{dj}^t (d3 = 1, \dots, D3)$ .

The smart sustainable development stage (S2) has F inputs,  $IN2_{fj}^t (f = 1, \dots, F)$ , and K desirable outputs,  $O2_{kj}^t (k = 1, \dots, K)$ .

The stages are connected through intermediate products (Links). Specifically,  $z1_{hj}^t (h1 = 1 \dots H1)$  denotes the intermediate products linking the infrastructure safety sub-stage (S1.1) to the smart sustainable development stage (S2);  $z2_{hj}^t (h2 = 1 \dots H2)$  denotes those linking the water safety sub-stage (S1.2) to S2; and  $z3_{hj}^t (h3 = 1 \dots H3)$  denotes those linking the food safety sub-stage (S1.3) to S2. In addition,  $c_{lj}^t (l = 1, \dots, L)$  denotes the carry-over variables linking consecutive periods. The specific input, output, link, and Carry-over variables corresponding to these notations are presented in Table 2.

The efficiency score of decision-making unit  $DMU_p$  is:

$$\max GFE = \sum_{t=1}^T (w_1^t \theta_1^t + w_2^t \theta_2^t) \quad (8)$$

Subject to:

S1.1 Infrastructure Safety Sub-stage:

$$\begin{aligned} \sum_j^n \lambda_{j1.1}^t IN11_{aj1.1}^t &\leq IN11_{ap1.1}^t - \theta_{1.1}^t g_{ap1.1}^t \quad \forall a1, t = 1, 2 \dots T \\ \sum_j^n \lambda_{j1.1}^t O11_{bj1.1}^t &\geq O11_{bp1.1}^t + \theta_{1.1}^t g_{bp1.1}^t \quad \forall b1, t = 1, 2 \dots T \\ \sum_j^n \lambda_{j1.1}^t U11_{dj1.1}^t &\leq U11_{dp1.1}^t - \theta_{1.1}^t g_{dp1.1}^t \quad \forall d1, t = 1, 2 \dots T \\ \sum_j^n \lambda_{j1.1}^t z1_{hj(1.1,2)}^t &\geq z1_{hp(1.1,2)}^t + \theta_{(1.1,2)}^t g_{hp(1.1,2)}^t \quad \forall h1, t = 1, 2 \dots T \end{aligned}$$

$$\sum_j^n \lambda_{j1.1}^t = 1 \quad \lambda_{j1.1}^t \geq 0 \quad \forall j, \quad t = 1, 2 \dots T$$

S1.2 Water Safety Sub-stage:

$$\sum_j^n \lambda_{j1.2}^t \text{IN}12_{a2j1.2}^t \leq \text{IN}12_{a2p1.2}^t - \theta_{1.2}^t g_{a2p1.2}^t \quad \forall a2, t = 1, 2 \dots T$$

$$\sum_j^n \lambda_{j1.2}^t \text{O}12_{b2j1.2}^t \geq \text{O}12_{b2p1.2}^t + \theta_{1.2}^t g_{b2p1.2}^t \quad \forall b2, t = 1, 2 \dots T$$

$$\sum_j^n \lambda_{j1.2}^t \text{U}12_{d2j1.2}^t \leq \text{U}12_{d2p1.2}^t - \theta_{1.2}^t g_{d2p1.2}^t \quad \forall d1, t = 1, 2 \dots T$$

$$\sum_j^n \lambda_{j1.2}^t z_{h2j(1.2,2)}^t \geq z_{h2p(1.2,2)}^t + \theta_{(1.2,2)}^t g_{h2p(1.2,2)}^t \quad \forall h2, t = 1, 2 \dots T$$

$$\sum_j^n \lambda_{j1.2}^t = 1 \quad \lambda_{j1.2}^t \geq 0 \quad \forall j, \quad t = 1, 2 \dots T$$

S1.3 Food Safety Sub-stage:

$$\sum_j^n \lambda_{j1.3}^t \text{IN}13_{a3j1.3}^t \leq \text{IN}13_{a3p1.3}^t - \theta_{1.3}^t g_{a3p1.3}^t \quad \forall a3, t = 1, 2 \dots T$$

$$\sum_j^n \lambda_{j1.3}^t \text{O}13_{b3j1.3}^t \geq \text{O}13_{b3p1.3}^t + \theta_{1.3}^t g_{b3p1.3}^t \quad \forall b3, t = 1, 2 \dots T$$

$$\sum_j^n \lambda_{j1.3}^t \text{U}13_{d3j1.3}^t \leq \text{U}13_{d3p1.3}^t - \theta_{1.3}^t g_{d3p1.3}^t \quad \forall d1, t = 1, 2 \dots T$$

$$\sum_j^n \lambda_{j1.3}^t z_{h3j(1.3,2)}^t \geq z_{h3p(1.3,2)}^t + \theta_{(1.3,2)}^t g_{h3p(1.3,2)}^t \quad \forall h3, t = 1, 2 \dots T$$

$$\sum_j^n \lambda_{j1.3}^t = 1 \quad \lambda_{j1.3}^t \geq 0 \quad \forall j, \quad t = 1, 2 \dots T$$

S2 Smart Sustainable Development Stage:

$$\sum_j^n \lambda_{j2}^t \text{IN}2_{fj2}^t \leq \text{IN}2_{fp2}^t - \theta_2^t g_{fp2}^t \quad \forall f, t = 1, 2 \dots T$$

$$\sum_j^n \lambda_{j2}^t \text{O}2_{kj2}^t \geq \text{O}2_{kp2}^t + \theta_2^t g_{kp2}^t \quad \forall k, t = 1, 2 \dots T$$

$$\sum_j^n \lambda_{j2}^t = 1 \quad \lambda_{j2}^t \geq 0 \quad \forall j, \quad t = 1, 2 \dots T$$

Intertemporal Links between Consecutive Periods:

$$\sum_{j=1}^n \lambda_j^{t-1} c_{ij}^t = \sum_{j=1}^n \lambda_j^t c_{ij}^t, \quad \forall i, \forall t$$

Where  $g_{a1p1.1}^t$ ,  $g_{b1p1.1}^t$ ,  $g_{d1p1.1}^t$  and  $g_{h1p(1.1,2)}^t$  denote the direction vectors associated with the inputs and outputs of Stage 1.1 and the intermediate outputs from Stage 1.1 to Stage 2;  $g_{a2p1.2}^t$ ,  $g_{b2p1.2}^t$ ,  $g_{d2p1.2}^t$  and  $g_{h2p(1.2,2)}^t$  denote the direction vectors associated with the inputs and outputs of Stage 1.2 and the intermediate outputs from Stage 1.2 to Stage 2;  $g_{a3p1.3}^t$ ,  $g_{b3p1.3}^t$ ,  $g_{d3p1.3}^t$  and  $g_{h3p(1.3,2)}^t$  denote the direction vectors associated with the inputs and outputs of Stage 1.3 and the intermediate outputs from Stage 1.3 to Stage 2;  $g_{fp2}^t$  and  $g_{kp2}^t$  denote the direction vectors associated with the inputs and desirable outputs of Stage 2;  $w_1^t$  and  $w_2^t$  denote the weights of Stages 1 and 2;  $\theta_1^t$  and  $\theta_2^t$  denote the efficiencies of Stages 1 and 2.

Based on the above model structure, Figure 1 presents the research framework of this study.

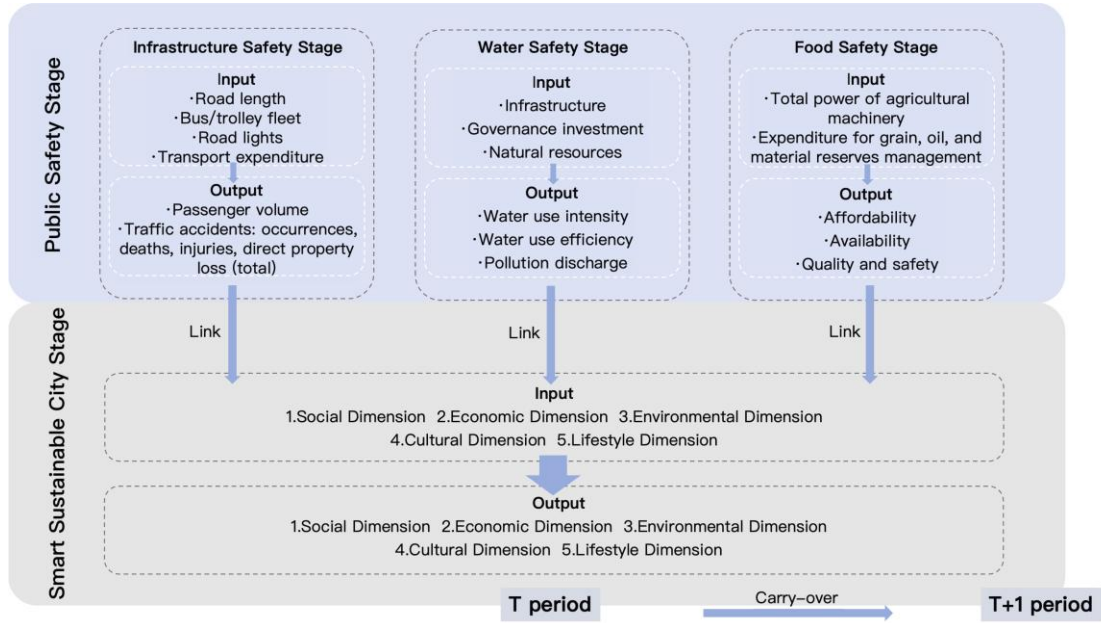


**Figure 1 Research Framework**

## 4. Empirical Results and Analysis

### 4.1 Data Description and Statistical Analysis

Considering data availability, this study selects sample data from 30 provinces, municipalities,

and autonomous regions in China from 2017 to 2023 (excluding Tibet, Hong Kong, Macao, and Taiwan) to examine the impact of public safety on the development of smart sustainable cities. Table 3 presents the study sample.

Table 4 presents the descriptive statistics of the data, where indicators marked with an asterisk (\*) are the fitted indicators. The data are obtained from the *China Statistical Yearbook*, *China Environment Statistical Yearbook*, *China Social Statistical Yearbook*, *China Statistical Yearbook on Culture and Related Industries*, the China Stock Market & Accounting Research Database (CSMAR), and the Chinese Research Data Services Platform (CNRDS).

**Table 3 Study Sample**

| DMUs                                                                                                                                                                                                                                                                            |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Beijing, Tianjin, Hebei, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong, Hainan, Inner Mongolia, Guangxi, Chongqing, Sichuan, Guizhou, Yunnan, Shaanxi, Gansu, Qinghai, Ningxia, Xinjiang, Shanxi, Anhui, Jiangxi, Henan, Hubei, Hunan, Liaoning, Jilin, Heilongjiang |

**Table 4 Descriptive Statistics of Indicators**

| Indicators                                                                                                     | Obs | Mean  | Std.  | Max   | Min     |
|----------------------------------------------------------------------------------------------------------------|-----|-------|-------|-------|---------|
| S1.1 Input Indicators*                                                                                         | 210 | 0.269 | 0.206 | 0.949 | 0.006   |
| S1.1 Desirable Output Indicators: Passenger Volume (10,000 persons)                                            | 210 | 0.295 | 0.233 | 1.000 | 0.00001 |
| S1.1 Undesirable Output Indicators*                                                                            | 210 | 0.760 | 0.182 | 0.988 | 0.099   |
| Link from S1.1 to S2: Passenger Volume (10,000 persons)                                                        | 210 | 0.295 | 0.233 | 1.000 | 0.00001 |
| S1.2 Input Indicators*                                                                                         | 210 | 0.197 | 0.118 | 0.688 | 0.018   |
| S1.2 Desirable Output Indicators:<br>Comprehensive Water Supply Capacity (10,000 m <sup>3</sup> /day)          | 210 | 0.217 | 0.207 | 1.000 | 0.00001 |
| S1.2 Undesirable Output Indicators*                                                                            | 210 | 0.714 | 0.161 | 0.987 | 0.308   |
| Link from S1.2 to S2:<br>Comprehensive Water Supply Capacity (10,000 m <sup>3</sup> /day)                      | 210 | 0.217 | 0.207 | 1.000 | 0.00001 |
| S1.3 Input Indicators*                                                                                         | 210 | 0.290 | 0.198 | 0.849 | 0.022   |
| S1.3 Desirable Output Indicators*                                                                              | 210 | 0.288 | 0.123 | 0.674 | 0.064   |
| S1.3 Undesirable Output Indicators:<br>Proportion of Children Under 5 with Moderate or Severe Malnutrition (%) | 210 | 0.610 | 0.152 | 0.998 | 0.144   |
| Link from S1.3 to S2*                                                                                          | 210 | 0.288 | 0.123 | 0.674 | 0.064   |
| S2 Social Dimension Input Indicators*                                                                          | 210 | 0.298 | 0.189 | 0.964 | 0.001   |
| S2 Social Dimension Output Indicators*                                                                         | 210 | 0.363 | 0.102 | 0.595 | 0.162   |
| S2 Economic Dimension Input Indicators*                                                                        | 210 | 0.296 | 0.203 | 0.856 | 0.018   |
| S2 Economic Dimension Output Indicators*                                                                       | 210 | 0.203 | 0.096 | 0.568 | 0.067   |

|                                                                                                |     |       |       |       |         |
|------------------------------------------------------------------------------------------------|-----|-------|-------|-------|---------|
| S2 Environmental Dimension Input:<br>Environmental Protection Expenditure (100 million CNY)    | 210 | 0.223 | 0.151 | 1.000 | 0.00001 |
| S2 Environmental Dimension Output Indicators*                                                  | 210 | 0.189 | 0.116 | 0.698 | 0.025   |
| S2 Cultural Dimension Input:<br>Culture, Sports & Media Expenditure (100 million CNY)          | 210 | 0.235 | 0.181 | 1.000 | 0.00001 |
| S2 Cultural Dimension Output Indicators*                                                       | 210 | 0.157 | 0.099 | 0.491 | 0.011   |
| S2 Lifestyle Dimension Input:<br>Urban & Rural Community Affairs Expenditure (100 million CNY) | 210 | 0.257 | 0.197 | 1.000 | 0.00001 |
| S2 Lifestyle Dimension Output Indicators*                                                      | 210 | 0.230 | 0.120 | 0.622 | 0.075   |
| Carry-over: Fixed Asset Investment (100 million CNY)                                           | 210 | 0.334 | 0.266 | 1.000 | 0.00001 |

Note: As some values are relatively small, five decimal places are retained.

## 4.2 Total Efficiency Analysis

### 4.2.1 Spatial Distribution of Total Efficiency

Total efficiency focuses on the co-evolution of urban public-safety governance and smart sustainable development, reflecting the dynamic balance level between urban public safety and smart sustainable development. Figure 2 presents the spatial distribution of total efficiency across 30 Chinese provinces during the study period. Overall, total efficiency is relatively low across the provinces. Only four provinces have efficiency values above 0.6, and none reaches the optimal efficiency level (Total Efficiency = 1). This indicates that most provinces have not achieved a dynamic balance between urban public safety and smart sustainable development, suggesting a potential trade-off between the two. Using the natural breaks method, all provinces are classified into three categories: low-efficiency provinces (0.179200 – 0.303300), medium-efficiency provinces (0.303301 – 0.498000), and high-efficiency provinces (0.498001 – 0.942500). Overall, low- and medium-efficiency regions exhibit a spatially contiguous and clustered distribution, whereas high-efficiency regions are more scattered. This pattern suggests a certain degree of spatial autocorrelation in regional efficiency: low- and medium-efficiency regions tend to cluster due to spatial proximity, while high-efficiency regions are more likely to exhibit polarized development driven by growth poles (Krugman, 1991; Anselin, 1995).

Specifically, the high-efficiency provinces include Ningxia, Qinghai, Hainan, Tianjin, and Beijing, which are relatively dispersed geographically. Ningxia and Qinghai are located in northwestern China and are characterized by relatively low population density and smaller urban systems, resulting in lower costs and coordination difficulties in public-safety governance and

making it easier to achieve higher overall governance efficiency. Meanwhile, in recent years, the two provinces have made notable progress in green transformation and sustainable development through ecological conservation and the development of new energy industries, providing a solid foundation for smart sustainable urban development. Hainan, an island province in southern China, constitutes a relatively independent geographical unit with clearly defined governance boundaries and lower coordination costs, facilitating the coordinated advancement of ecological protection and regional safety governance (Kelman et al., 2021). In addition, the development of the Hainan Free Trade Port has accelerated improvements in digital governance and smart-city development. Tianjin and Beijing are located within the capital economic region, where a strong economic foundation and a high concentration of technological innovation resources have enabled them to outperform other regions in smart governance, digital infrastructure, and the application of public-safety technologies.

Medium-efficiency provinces form two discontinuous belt-like patterns across northern and southern China. The northern belt covers Xinjiang and Gansu in northwestern China, Shanxi in northern China, and Liaoning in northeastern China. These regions contain a relatively high concentration of resource-based cities and have a strong heavy-industry base, providing a solid material foundation for infrastructure development and public-safety provision. However, they generally face imbalanced industrial structures and a high dependence on natural resources, leaving considerable room for improvement in green transformation and smart development.

The southern belt covers southwestern China (Yunnan, Guizhou, Guangxi, and Chongqing) and the southeastern coastal region (Fujian and Zhejiang). Benefiting from their relatively advanced digital economies and strong foundations for an open economy, Fujian and Zhejiang perform well in smart-city development and the digitalization of public services. However, compared with the leading provinces of Beijing and Tianjin, they remain somewhat weaker in their overall capacity to attract and concentrate resources. Some southwestern regions have gained a certain latecomer advantage in smart-city development from sustained national investment in digital infrastructure in recent years, but they remain constrained by complex geographical conditions and relatively weak infrastructure, and their total efficiency has yet to reach the top tier.

Low-efficiency provinces exhibit a large-scale contiguous distribution, covering the eastern coastal and central inland regions and extending to northeastern China (Heilongjiang and Jilin) and

Sichuan in southwestern China. This group includes economically developed eastern coastal provinces (Jiangsu, Shandong, Guangdong, Shanghai, and Hebei) as well as a broad range of central inland provinces (Henan, Hubei, Hunan, Jiangxi, and Anhui). Although these regions have relatively large economies, their high concentrations of population, industries, and urban activities place greater pressure on public-safety governance and resource coordination, potentially leading to infrastructure overload, water-resource constraints, and increasingly complex food-safety regulation. In addition, some central and northeastern provinces continue to face a relatively high share of traditional industries and uneven progress in digital and green transformation, constraining their transition toward smart sustainable development.

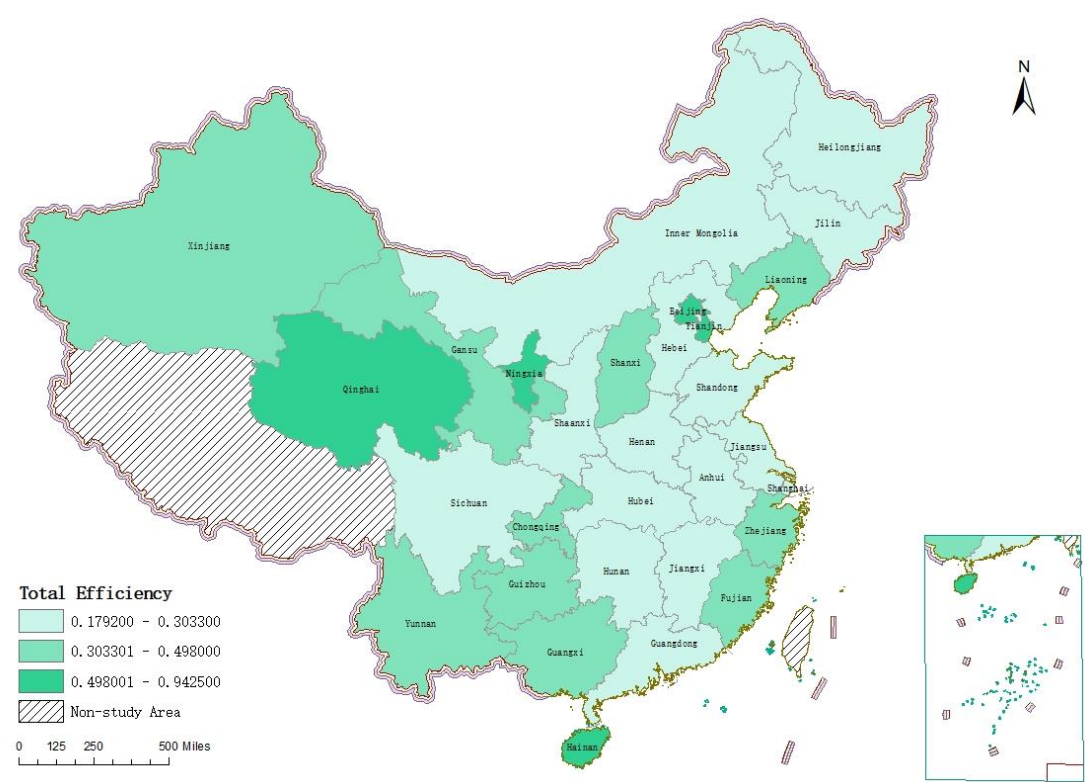


**Figure 2 Spatial Distribution of Total Efficiency**

#### 4.2.2 Dynamic Changes in Total Efficiency

To provide a more intuitive description of the distribution characteristics and dynamic evolution of total efficiency (the dynamic balance level between urban public safety and smart sustainable development) across 30 Chinese provinces, this study employs kernel density estimation to depict the distribution of total efficiency across the provinces. Four years at two-year intervals, namely 2017, 2019, 2021, and 2023, are selected as observation points to examine the dynamic

changes in total efficiency during the study period, as shown in .

2017 – 2019: In terms of distributional shape, the kernel density curves of total efficiency in both 2017 and 2019 exhibit a unimodal distribution with a right tail, indicating that total efficiency across provinces was relatively concentrated at a moderately low level with limited regional disparities during this period. Compared with 2017, the peak of the 2019 curve is narrower and higher, reflecting more pronounced efficiency improvements among provinces in the low-to-medium efficiency range. In terms of distributional position, the center of the curve shifts to the right from 2017 to 2019, with the efficiency level corresponding to the peak increasing from approximately 0.35 to 0.42. This indicates an overall upward trend in the dynamic balance level between urban public safety and smart sustainable development across regions during this period.

2019 – 2021: In terms of distributional shape, the curve in 2021 exhibits a bimodal pattern, with the left peak significantly higher than the right peak and lower and wider than the peak in 2019. This indicates that provinces in the low-to-medium efficiency range still constitute a relatively large group, while also suggesting that some provinces, such as Beijing, Tianjin, and Shanxi, made notable progress in public-safety governance and smart sustainable urban development in 2021, thereby moving out of the original low-to-medium efficiency group. In terms of distributional position, the center of the curve shifts slightly to the right in 2021, with the left and right peaks corresponding to efficiency levels of approximately 0.5 and 0.7, respectively. This suggests an increasingly uneven distribution of the dynamic balance level between urban public safety and smart sustainable development across regions, with more provinces reaching medium and high efficiency levels than before.

2021 – 2023: In terms of distributional shape, the curve in 2023 returns to a unimodal pattern, but its peak becomes markedly narrower and higher, while the right tail exhibits an irregular shape. This pattern of a sharp left peak combined with a wavy right tail suggests a substantial decline in total efficiency across most provinces. In terms of distributional position, the center of the 2023 curve shifts considerably to the left, with the efficiency level corresponding to the peak falling to approximately 0.38. This indicates that the total efficiency of most provinces declined simultaneously to around 0.38 between 2021 and 2023. This decline may have resulted from the combined effects of widespread shocks, particularly the lagged effects of the COVID-19 pandemic (Fang et al., 2025) and the extreme heat and drought events in 2022. On the one hand, slower

economic recovery and mounting fiscal pressures in the post-pandemic period constrained investment in public safety and smart-city development in some regions. On the other hand, extreme drought further disrupted water resources, energy supply, and food production, contributing to a simultaneous decline in efficiency across most provinces. Only a small number of provinces, including Beijing, Tianjin, Qinghai, Hainan, and Ningxia, maintained relatively high efficiency levels, indicating their stronger capacity to recover from such shocks.

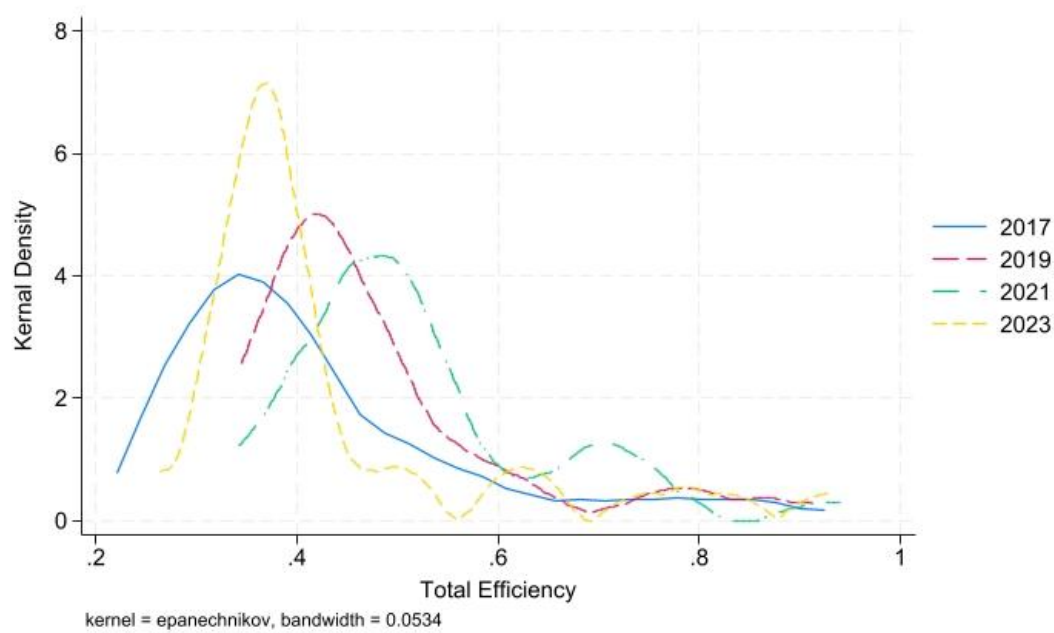


**Figure 3 Kernel Density Plot of Total Efficiency across China**

### 4.3 Stage Efficiency Analysis

#### 4.3.1 Inter-stage Efficiency Relationships

As described above, this study takes public safety, consisting of three parallel sub-stages, namely S1.1 Infrastructure Safety, S1.2 Water Safety, and S1.3 Food Safety, as the first stage, and smart sustainable development (S2) as the second stage, thereby examining the impact of public safety on smart sustainable urban development. Accordingly, this section focuses on stage efficiency to examine heterogeneous performance across different dimensions of public safety. Bubble charts are constructed with the efficiency values of S1.1, S1.2, and S1.3 on the x-axis, respectively, the efficiency value of S2 on the y-axis, and total efficiency represented by bubble size. Using the median as the dividing criterion, each chart is divided into four quadrants: Quadrant I (high – high), Quadrant II (low – high), Quadrant III (low – low), and Quadrant IV (high – low), as shown in

Figure 4. This allows for a more detailed analysis of how different dimensions of public safety affect smart sustainable urban development and identifies which safety deficiencies constitute critical constraints on such development.

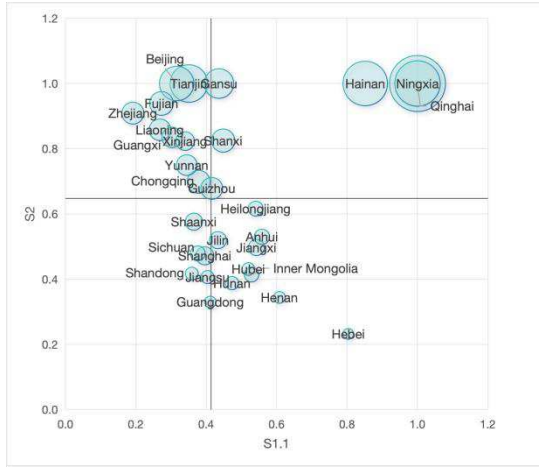
S1.1 & S2 (Figure 4-1): Compared with the other two bubble charts, Figure 4-1 exhibits the most dispersed distribution of bubbles, with no clear distributional pattern. It also contains the largest number of provinces in Quadrant IV, indicating that many provinces have above-median S1.1 efficiency but below-median S2 efficiency. This suggests that a high level of infrastructure safety governance does not necessarily translate into strong performance in smart sustainable urban development. There may be two main reasons for this pattern. On the one hand, regions such as Hebei, Henan, Inner Mongolia, and Hunan have long relied on investment in traditional infrastructure to drive economic growth (Ouattara & Zhang, 2019), while investment in digital infrastructure and smart governance platforms has remained relatively limited. Combined with insufficient reserves of digital talent and limited experience in smart operations, existing smart-city initiatives have struggled to form effective synergies with established infrastructure. On the other hand, regions such as Shanghai, Jiangsu, and Guangdong face transformation constraints arising from their large stocks of existing infrastructure. Having undergone industrialization and urbanization relatively early, these regions have developed mature and stable infrastructure systems, making smart upgrading more costly and creating greater challenges in system compatibility. Ultimately, both situations result in relatively high infrastructure safety but insufficient conversion into smart sustainable development.

S1.2 & S2 (Figure 4-2): Compared with the other two bubble charts, Figure 4-2 shows the most even distribution of bubbles across the four quadrants, indicating a relatively weak correlation between S1.2 and S2. A closer examination suggests two possible explanations. On the one hand, water safety is a necessary but not sufficient condition for smart sustainable urban development, supporting the aforementioned assumption that public safety constitutes a non-negotiable foundation. Risks such as flooding and water-supply crises can directly constrain the stable operation of smart urban systems. However, meeting this basic safety threshold does not automatically lead to a high level of smart sustainable development; it also requires the deep integration of conventional water safety management with smart urban governance platforms. On the other hand, a certain substitution effect may exist among the three parallel sub-stages. For

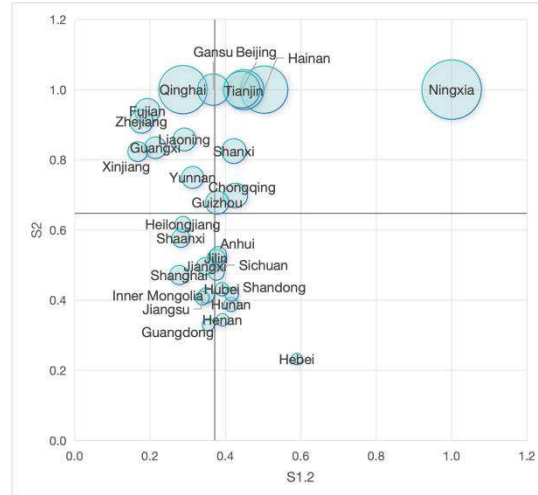
example, smart infrastructure (S1.1), such as intelligent control systems for sponge cities, may compensate for deficiencies in water safety (S1.2). This further demonstrates that public safety is a complex system composed of multiple interconnected and interacting subsystems (Liu et al., 2017). By adopting a model with three parallel sub-stages, this study opens the "black box" of public safety and identifies the heterogeneous effects of different dimensions of public safety on smart sustainable urban development.

S1.3 & S2 (Figure 4-3): Compared with the other two bubble charts, Figure 4-3 shows more bubbles located in Quadrants I and III, indicating that a larger number of provinces exhibit either high efficiency in both S1.3 and S2 or low efficiency in both. This suggests a relatively clear positive correlation between food safety and smart sustainable urban development, indicating that high food-safety efficiency can translate into high efficiency in smart sustainable development. At the same time, most bubbles are concentrated toward the left side of the chart, indicating that S1.3 efficiency is generally low across provinces, with a median of only 0.2647. Taken together, these two characteristics suggest that deficiencies in food safety constitute a key factor constraining smart sustainable urban development. Traditional food-safety governance has long been characterized by an ex post remedial approach, relying primarily on accountability, product recalls, and intensive rectification after incidents occur rather than full-cycle risk prevention (Liu et al., 2019). As a result, greater human and material resources are devoted to incident management and emergency response, thereby weakening cities' capacity for digital, smart, and sustainable transformation.

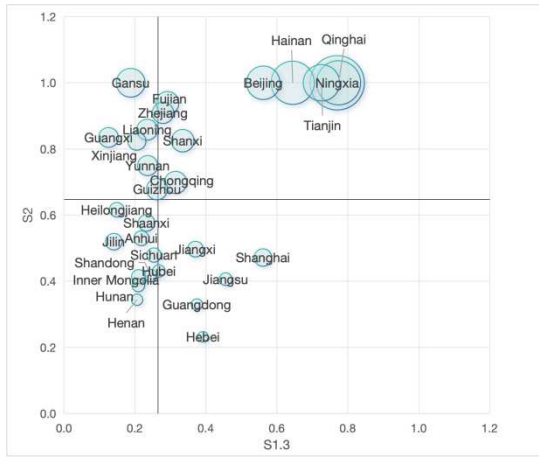
S2 & TE (Figure 4-4): Compared with the sub-stages of S1, provinces generally exhibit higher efficiency in S2, with a median of 0.6473, indicating that most provinces perform well in smart sustainable urban development. Meanwhile, larger bubbles in the three bubble charts are more frequently concentrated in the upper part of the charts (Quadrants I and II), suggesting that higher S2 efficiency may also lead to higher total efficiency. To further examine this pattern, a scatter plot of S2 efficiency and total efficiency is constructed. The trend line in Figure 4-4 also indicates a positive correlation between smart sustainable urban development and total efficiency. This suggests that promoting the smart and sustainable transformation of cities can effectively improve the dynamic balance level between urban public safety and smart sustainable development.



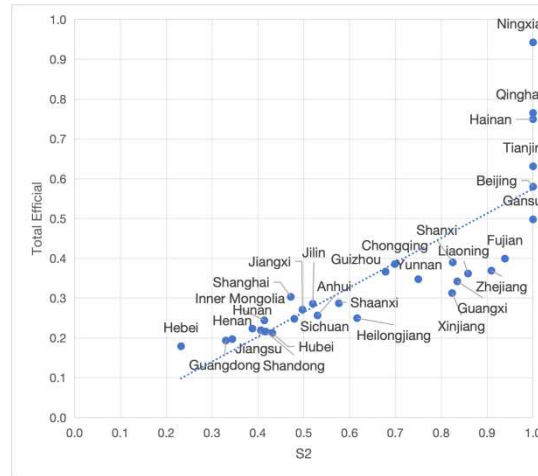
(1) Bubble Chart of S1.1 & S2



(2) Bubble Chart of S1.2 & S2



(3) Bubble Chart of S1.3 & S2



(4) Scatter Plot of S2 & TE

**Figure 4 Bubble Charts of Stage Efficiency**

Finally, based on a comprehensive analysis of the three bubble charts, the 30 provinces can be classified into five categories, as shown in Table 5.

(1) High – High Type. This category includes four provinces, such as Guizhou and Hainan, whose bubbles are located in Quadrant I in all three bubble charts. This indicates that the efficiency values of all S1 sub-stages and S2 are above their respective medians, reflecting coordinated and mutually reinforcing development between urban public safety and smart sustainable development. These provinces should maintain their existing advantages.

(2) Low – High Type. This category includes seven provinces, such as Zhejiang and Liaoning, whose bubbles are mostly located in Quadrant II, with none falling into Quadrants III or IV. This

indicates that the efficiency of the S1 sub-stages is generally low, while S2 efficiency is relatively high, suggesting that urban public-safety governance lags behind smart sustainable development. These provinces should address their safety deficiencies and strengthen urban risk prevention and emergency response capabilities.

(3) High – Low Type. This category includes 14 provinces, such as Hebei and Henan, whose bubbles appear in Quadrant IV in at least one of the three bubble charts. This indicates that the efficiency of at least one S1 sub-stage is above the median, while S2 efficiency is relatively low, suggesting that smart sustainable urban development lags behind public-safety governance. These provinces should accelerate digital transformation and green and low-carbon development while consolidating their achievements in safety governance, thereby generating synergies between safety and development.

(4) Low – Low Type. This category includes only Shaanxi, whose bubbles are located in Quadrant III in all three bubble charts. The efficiency values of all S1 sub-stages and S2 are below their respective medians, resulting in relatively low overall efficiency and indicating the need for systematic improvement.

(5) Unbalanced Type. This category includes four provinces, such as Beijing and Tianjin, whose bubbles are mostly located in Quadrant I, with none falling into Quadrants III or IV. This indicates uneven efficiency across the S1 sub-stages, with weaknesses in certain dimensions, while S2 efficiency remains relatively high. These provinces should therefore target and strengthen their weaker areas.

**Table 5 Classification of Provinces**

| No. | Type           | Number | Provinces                                                                          | Quadrant Distribution                                           | Efficiency Implications                                                                            |
|-----|----------------|--------|------------------------------------------------------------------------------------|-----------------------------------------------------------------|----------------------------------------------------------------------------------------------------|
| (1) | High–High Type | 4      | Guizhou, Hainan, Ningxia, Shanxi                                                   | All located in Quadrant I                                       | Efficiency values of all S1 sub-stages and S2 are above their respective medians                   |
| (2) | Low–High Type  | 7      | Zhejiang, Liaoning, Guangxi, Xinjiang, Fujian, Yunnan, Gansu                       | Mainly located in Quadrant II, with none in Quadrants III or IV | Efficiency of the S1 sub-stages is generally low, while S2 efficiency is relatively high           |
| (3) | High–Low Type  | 14     | Hebei, Henan, Guangdong, Hubei, Hunan, Jiangxi, Anhui, Jiangsu, Shanghai, Sichuan, | All include Quadrant IV                                         | Efficiency of at least one S1 sub-stage is above the median, while S2 efficiency is relatively low |

|     |                 |   |                                               |                                                                |                                                                                                                              |
|-----|-----------------|---|-----------------------------------------------|----------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------|
|     |                 |   | Jilin, Heilongjiang, Inner Mongolia, Shandong |                                                                |                                                                                                                              |
| (4) | Low-Low Type    | 1 | Shaanxi                                       | All located in Quadrant III                                    | Efficiency values of all S1 sub-stages and S2 are below their respective medians, with relatively low overall efficiency     |
| (5) | Unbalanced Type | 4 | Beijing, Tianjin, Chongqing, Qinghai          | Mainly located in Quadrant I, with none in Quadrants III or IV | Efficiency across the S1 sub-stages is uneven, with weaknesses in certain dimensions, while S2 efficiency is relatively high |

#### 4.3.2 Dynamic Analysis of Stage Efficiency

The efficiency values of the 30 provinces are averaged for each stage in each year, and the resulting annual stage efficiency trends are plotted in Figure 5 to illustrate changes in stage efficiency over time. Furthermore, the efficiency curves of the S1 sub-stages are compared separately with the S2 efficiency curve to clarify the dynamic interactions between the public safety sub-stages and the smart sustainable development stage.

As shown in Figure 5, S2 efficiency is substantially higher than S1.1 efficiency, while S1.1 efficiency is slightly higher than S1.2 and S1.3 efficiency. Specifically:

S2 (Smart Sustainable Development Stage): Efficiency remains relatively stable overall, fluctuating around 0.65, but declines markedly from 2020 to 2021, followed by a rapid recovery from 2021 to 2022. This pattern may reflect the immediate shock of the COVID-19 pandemic. Although efficiency recovered rapidly afterward, it did not return to the peak level observed around 2018 (0.7315), suggesting that the lingering effects of the pandemic had not yet fully dissipated.

S1.1 (Infrastructure Safety Sub-stage): Efficiency exhibits a trend of continuous increase followed by a sharp decline, with the turning point likewise occurring around 2021. One possible explanation is the extraordinary investment in infrastructure following the outbreak of the COVID-19 pandemic in 2020, including temporary hospitals, nucleic acid testing sites, and standardized upgrades of fever clinics. Such extraordinary investment in pandemic-response infrastructure directly increased S1.1 efficiency. As pandemic-response resources were gradually withdrawn after 2022, S1.1 efficiency declined to approximately 0.46, but remained above its initial level of around 0.30. This may be because the permanent infrastructure accumulated during the pandemic has been transformed into a structural increase in infrastructure capacity.

S1.2 (Water Safety Sub-stage): Efficiency exhibits a fluctuating downward trend, with a small

peak around 2021, followed by a further decline to below its initial level. From a long-term perspective, gradually accumulating risks, including groundwater overexploitation, non-point source pollution, aging water-supply networks, and the slow accumulation of emerging contaminants, have continuously eroded the effectiveness of water-safety governance, resulting in a fluctuating decline in efficiency (Vorosmarty et al., 2015). From a short-term perspective, the small peak around 2021 may be attributed to extreme climate events, such as the catastrophic “7 • 20” rainstorm in Zhengzhou, Henan Province, in July 2021, which sharply increased investment in water-safety governance. As post-disaster emergency water supply was restored and repairs to water-supply networks were completed, efficiency subsequently declined again.

S1.3 (Food Safety Sub-stage): Efficiency exhibits pronounced fluctuations, with small peaks around 2019 and 2021, while the efficiency levels at the beginning and end of the study period remain broadly similar at approximately 0.30. This pattern suggests that food-safety governance in China may still be characterized, to some extent, by an event-driven approach. Following food-safety incidents, targeted rectification campaigns are often launched intensively; however, as public attention subsides and regulatory intensity weakens, food-safety governance also gradually relaxes (Wang et al., 2023). A normalized and institutionalized approach centered on risk prevention remains underdeveloped, with limited substantive progress achieved to date.

A comparative analysis of the four curves is conducted to examine the dynamic interactions between the public safety sub-stages and the smart sustainable development stage. Overall, the efficiency curves of the S1 sub-stages tend to fluctuate inversely with the S2 efficiency curve. The efficiency curves of S1.2 and S2 exhibit a particularly pronounced trade-off pattern, with one tending to rise as the other falls. Although S1.3 shows relatively small fluctuations, its overall trend also moves inversely to that of S2. In contrast, during 2017 – 2018 and 2022 – 2023, the efficiency curves of S1.1 and S2 move in the same direction, either rising or falling together. This may be because the smart and sustainable transformation of cities depends on the stable operation of smart infrastructure, suggesting that, in the absence of major external shocks, improvements in infrastructure safety can positively contribute to smart sustainable urban development.

Focusing on years with abnormal fluctuations, the inverse movements between the efficiency curves of the S1 sub-stages and S2 are most pronounced around 2021, when the lowest point of S2 and the highest points of the S1 sub-stages occur within the same period. This indicates that Chinese

provinces have not yet achieved synergistic development between public-safety governance and smart sustainable urban development. When confronted with major external shocks, resources tend to be prioritized for remedial safety governance, thereby crowding out resources and capacity for smart sustainable urban development. On the one hand, this once again demonstrates that safety constitutes a non-negotiable foundation for smart sustainable cities. On the other hand, it highlights the importance of strengthening urban risk resilience and building resilient cities. It is therefore necessary to shift from ex post remediation to ex ante prevention and integrate public safety into the design framework of smart sustainable cities, thereby preventing the accumulation of safety risks from constraining sustainable urban development.

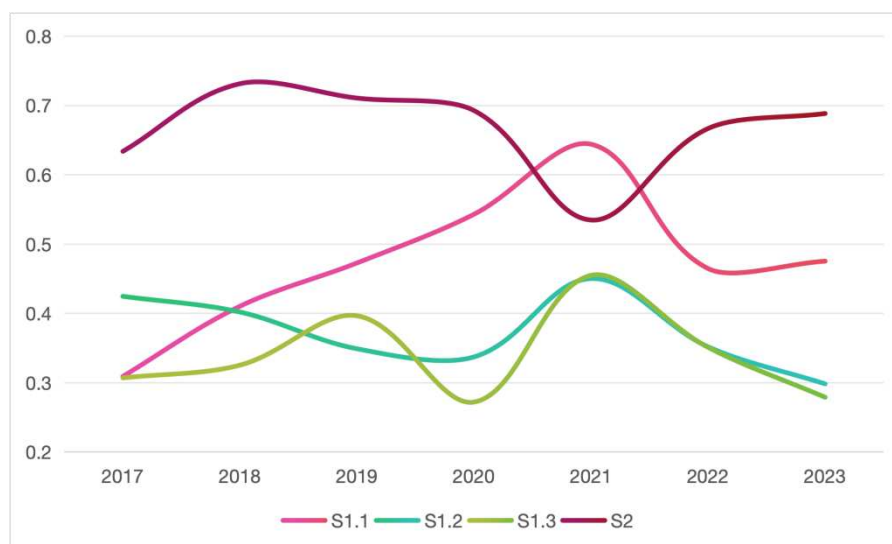


**Figure 5 Annual Trends in Stage Efficiency**

## 5. Conclusions and Policy Recommendations

To examine the relationship between urban public safety and smart sustainable development, this study used sample data from 30 Chinese provinces, municipalities and autonomous regions (excluding Tibet, Hong Kong, Macao, and Taiwan) for 2017–2023. Using the Entropy Three Parallel Two-stage Dynamic DDF model, it treated public safety as the first stage, comprising three parallel sub-stages: infrastructure safety, water safety and food safety. Smart sustainable development was treated as the second stage. The model was used to assess the dynamic balance level between public safety governance and smart sustainable development and to clarify the differentiated effects of public safety across dimensions. The main conclusions are as follows:

(1) Overall, most provinces have not achieved a dynamic balance between public safety and smart sustainable development. Regions with medium-to-low efficiency exhibit spatial clustering,

whereas high-efficiency regions are relatively dispersed. High-efficiency regions generally benefit from ecological-protection outcomes, green-industry development and access to economic and innovation resources; in some cases, their high efficiency may also be associated with relatively self-contained spatial units, whose clear governance boundaries help reduce the costs of cross-regional coordination. Low-efficiency regions are more constrained by a combination of resource dependence, delayed industrial transformation, complex geographical conditions, insufficient infrastructure capacity and the high-density concentration of population and economic activity. From a dynamic-evolution perspective, the dynamic balance level first increased and then declined, with a turning point around 2021. This pattern may reflect the combined effects of delayed effects of the pandemic and the extreme heat and drought events that occurred in 2022.

(2) Different dimensions of public safety have markedly different effects on smart sustainable development. Inadequate food-safety governance is a key constraint on improving the level of smart sustainable development in cities. Event-driven governance often directs limited resources towards accident handling and emergency response, potentially reducing the resources available for digitalization, intelligent transformation and sustainability. Improvements in infrastructure-safety governance have not yet generated sufficient momentum for smart sustainable development. Water safety appears to exhibit a threshold effect: meeting basic safety requirements does not necessarily produce a simultaneous improvement in smart sustainable development. In addition, the safety dimensions exhibit some substitution effects, such that strengths in one area may partly compensate for weaknesses in another.

(3) The governance levels of the different public-safety dimensions display distinct dynamic patterns. Infrastructure safety rose in the early years before declining, but remained above its initial level, suggesting that the improvements show some persistence. Water safety fluctuated downward, indicating that, in addition to extreme events, attention should be paid to gradual risks such as groundwater over-extraction, diffuse-source pollution, ageing water-supply networks and the accumulation of emerging contaminants. Food safety showed pronounced fluctuations, suggesting that event-driven governance has not yet been fundamentally transformed. Moreover, the interaction process shows that the three types of safety governance and smart sustainable development exhibited generally opposite fluctuation trends during the sample period, indicating that public safety governance and smart sustainable development have not yet formed a stable pattern of

coordinated development.

Based on these findings, the following policy recommendations are proposed:

(1) Establish a full-cycle governance system that coordinates safety and development and strengthens urban resilience. Public safety governance should move beyond the traditional approach that confines safety protection to disaster response and separates urban development and construction from risk prevention. Risk prevention should be embedded throughout urban planning, construction, operation and renewal, thereby linking risk identification, source control, emergency response, recovery and improvement with urban development in a full-cycle governance system. At the planning stage, the allocation of shelters, emergency supplies and response forces should be optimized on the basis of hazard mechanisms, risk-transmission pathways and urban vulnerability. During construction, operation and renewal, engineering monitoring, facility maintenance, business continuity management and safety requirements for the renewal of ageing urban areas should be implemented simultaneously to ensure that essential urban functions continue to operate under shocks.

(2) Expand the role of public safety governance from risk prevention to development support and foster constructive interaction between safety governance and smart sustainable development. Data resources, resilient infrastructure and collaborative networks generated through safety governance should serve as the basis for transforming risk-prevention capacity into capabilities for urban sensing, intelligent dispatch, green operation and improved public services. In this way, safety investment can serve not only to reduce risk-related losses but also to provide a stable operational foundation for smart sustainable development.

(3) Identify weaknesses in public-safety governance and implement targeted measures by domain. For infrastructure safety governance, the transition from incremental urban expansion to quality improvement and efficiency enhancement in existing urban areas should be used as an opportunity to coordinate facility renewal and operational governance through urban regeneration (Zhu et al., 2025). At the hardware level, priority should be given to the inspection, repair and upgrading of urban lifeline systems. At the software level, a full life-cycle management mechanism should cover infrastructure planning and construction, operation and maintenance, and emergency response.

For water-safety governance, differentiated approaches should be adopted according to the

speed of risk evolution and the mechanisms through which hazards occur: acute risks should be managed with prevention prioritized over rescue, whereas chronic risks should be managed with remediation prioritized over prevention. Sudden water-related disasters triggered by drought, intense rainfall and flooding develop rapidly, cause severe damage and leave only a short response window; prevention should therefore be prioritized (Christian et al., 2024). By contrast, slowly developing water-resource risks arising from long-term changes in temperature and precipitation, persistent groundwater over-extraction, ageing networks, accumulated diffuse-source pollution and the spread of emerging contaminants are often concealed, have long latency periods and accumulate gradually. They may become evident only after carrying-capacity thresholds are exceeded, so remediation should be prioritized over prevention (UN-Water, 2021).

For food-safety governance, regulation should adapt to longer supply chains, changing business models and faster risk transmission by shifting from a focus on end-point response towards resilient, full-chain supervision covering sources, processes and end points (FAO & WHO, 2022). Technological support should be used to improve risk perception and precision regulation, while governance capacity should be strengthened through clear responsibilities and institutional coordination.

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**Data Availability:** The dataset used in this study is provided as a Supplementary File. We do not analyse or generate any datasets, because our work proceeds within a theoretical and mathematical approach. One can obtain the relevant materials from the references below.

**Ethical Approval:** This article does not contain any studies with human participants performed by any of the authors.

**Informed Consent:** Not applicable.

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