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Demolition waste from the infrastructure network in China: Retrospective and perspective

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ABSTRACT

Infrastructure demolition waste (IDW) plays a crucial role in waste recycling and reuse. However, the sources and spatiotemporal distribution of IDW in China remain insufficiently understood. To address this gap, we develop a provincial IDW assessment model to analyze the spatiotemporal distribution patterns and evolutionary trends of IDW from 1949 to 2100. Our findings reveal pronounced regional disparities in IDW distribution between southern and northern provinces. Notably, Guangdong, Sichuan, and Shandong collectively contributed 15.49 %–24.25 % of the national IDW annually over the study period. The total IDW in China follows a volatile trajectory, increasing from 110.20 Mt in 2000 to a peak range of 317.43–1084.72 Mt around 2050, before declining to 59.72–393.12 Mt by 2100. Moreover, strategies such as extending the lifespan of infrastructure and improving material recycling rates are projected to reduce IDW by 46.07 % in 2050 and 74.64 % in 2100.

1. Introduction

During the accelerating urbanization and modernization process in China, continuous construction and demolition activities involving buildings and infrastructure have led to a rapid surge in construction and demolition waste generation (Lanau et al., 2019). China now produces over 2 billion tons of construction and demolition waste annually, accounting for approximately 40 % of its municipal solid waste. This substantial contribution to urban waste highlights the urgent need for sustainable practices in the construction and infrastructure sectors (Mohurd, 2021). However, the recovery rate of construction and demolition waste in China remains alarmingly low at just 10 % (Yu et al., 2022), in stark contrast to recovery rates exceeding 90 % in countries such as Germany, Japan, and South Korea (Ma and Hao, 2024). This discrepancy is largely attributed to the lack of clarity regarding the sources and spatiotemporal distribution of construction and demolition waste (Zhang et al., 2023). The challenge is particularly pronounced for infrastructure demolition waste (IDW), a major component of construction and demolition waste in China (Dai and Yue, 2023).

Investigating IDW is fraught with challenges, including limited data availability and poorly understood spatial-temporal distribution at the provincial level (Li et al., 2023). Examining these characteristics is essential for formulating targeted policies, advancing the recycling of demolition waste, and enhancing material utilization in China.

Material Flow Analysis (MFA) provides a robust framework for assessing construction and demolition waste by enabling the tracking of historical trends and future trajectories in material utilization within human society (Liang et al., 2023). While dynamic MFA models have been developed to evaluate demolition waste from buildings and infrastructure in China, and the existing researches primarily focus on the national scale (Shi et al., 2012; Wang et al., 2015) or city scale (Dai and Yue, 2023; Huang et al., 2017). Some studies employ high spatial resolution approaches based on geographic information systems (Cai et al., 2024; Gao et al., 2020; Long et al., 2024; Mao et al., 2020). These analyses predominantly emphasize buildings, categorized as residential and non-residential, while transportation infrastructure (e.g. expressways, highways, and railways) is treated as a supplementary element to broaden the research scope. However, if buildings represent the “flesh” of cities, then transportation and pipeline infrastructure constitute the “bones” that enhance the stability and functionality of urban systems. As such, this infrastructure plays an increasingly critical role in advancing high-quality urban development.

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Research on IDW dynamics within infrastructure backbone networks has gained traction at national and city levels. For example, studies have been conducted in countries like France (Nguyen and Kim, 2024), Vietnam (Nguyen et al., 2019), Pakistan (Shuker Ullah et al., 2024), the United States (Miatto et al., 2017), and 24 European countries (Nguyen et al., 2023). City-level analyses, such as those in Paris (Augiseau and Kim, 2021) and Hanoi (Bide et al., 2023), emphasize the importance of effective information management to address the challenges posed by rapid infrastructure construction and renewal. In China, Wen and Li (2010) investigated waste generated by ordinary highways between 2001 and 2005, revealing substantial obstacles to resource utilization and environmental sustainability. Shi et al. (2012) and Hou et al. (2015) projected IDW quantities from expressways, highways, railways, and sewage pipelines through 2050, highlighting infrastructure lifespan extensions as an effective strategy to reduce demolition waste. Additionally, city-level studies, such as Han et al. (2018) on Shanghai's waste material flows from 1980 to 2010, and Song et al. (2021), which developed a comprehensive database of IDW for 31 provinces from 1978 to 2018, have provided valuable insights for policy-making toward sustainable development. A detailed summary of existing IDW research is included in Table S1 in the Supplementary materials.

Despite these efforts, most studies focus on either estimating future demolition waste at the national level or analyzing historical trends at the provincial level. These approaches offer preliminary insights into IDW evolution but fall short of capturing the substantial variability in future infrastructure development plans across provinces. Addressing this gap requires concurrently assessing demolition demands and new construction requirements to facilitate a comprehensive evaluation of recycling and material utilization strategies.

To this end, we establish a provincial IDW assessment model that incorporates infrastructure development plans across China's 31 provinces and benchmarks IDW levels against those observed in developed countries. This model examines the spatial-temporal distribution and evolution of IDW from 1949 to 2100, covering diverse infrastructure types such as expressways, ordinary highways, urban roads, railways, subways, and pipelines for water supply, sewage, heat supply, and gas.

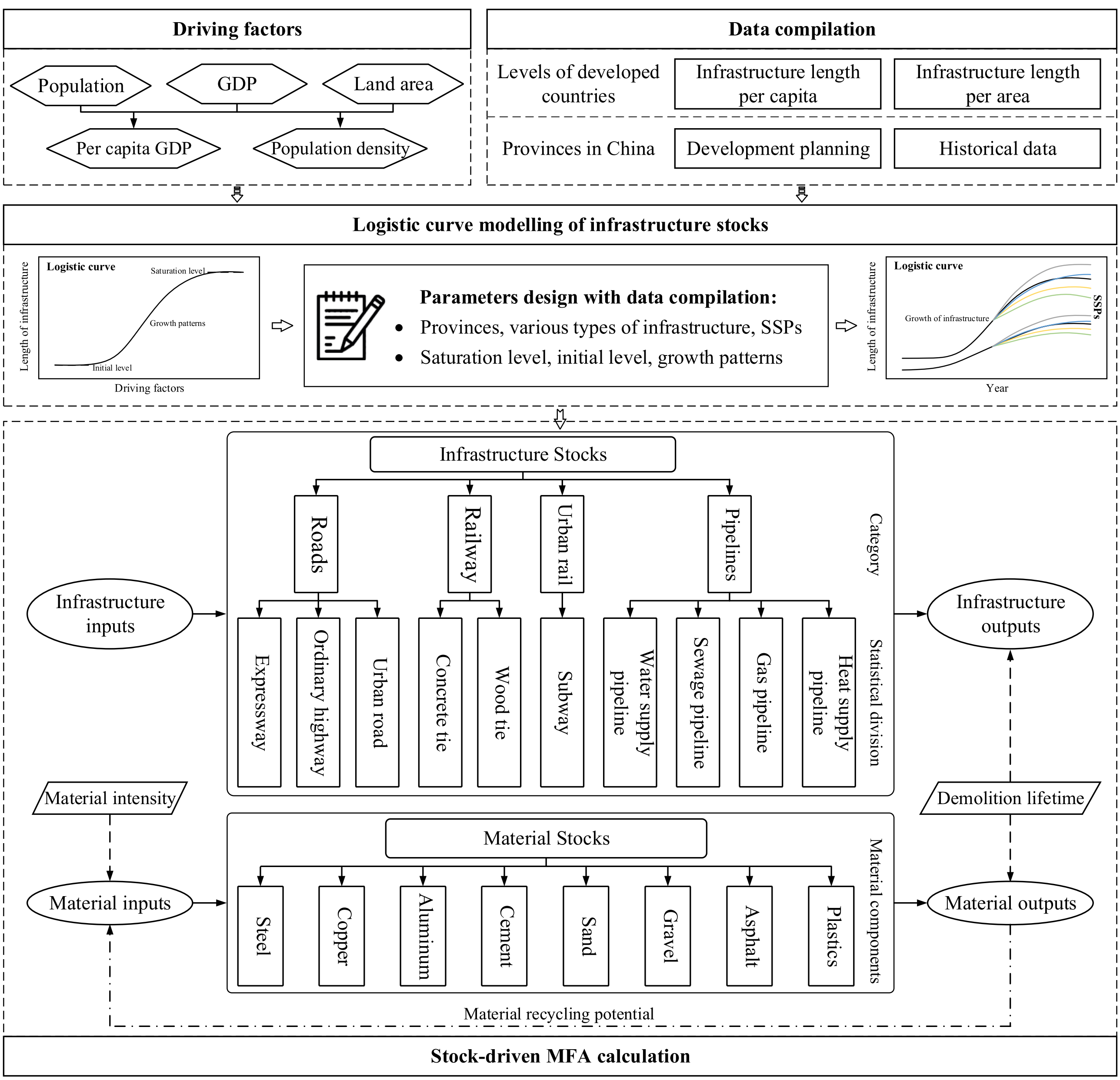

Fig. 1. Provincial IDW assessment model framework.

Additionally, we explore the primary materials involved, including steel, copper, aluminum, cement, sand, gravel, asphalt, and plastics. The potential for recycling demolition waste within infrastructure material metabolism is thoroughly investigated, supported by a multi-scenario analysis of dynamic IDW trajectories. The principal contributions of this study are as follows:

First, we develop a provincial IDW assessment model to project the evolution of IDW across China's provinces through 2100, focusing on diverse infrastructure types and materials. Second, we analyze the spatial-temporal distribution of IDW and explore the potential for circular material metabolism, incorporating future infrastructure construction demands. Third, we conduct a multi-scenario analysis to evaluate the impacts of various socioeconomic pathways, including variations in infrastructure lifespans and material recycling rates, on IDW trajectories.

The manuscript is organized as follows: Section 2 introduces the provincial IDW assessment model, grounded in the MFA methodology. Section 3 outlines the data sources used in this study. Section 4 examines the spatial-temporal evolution and distribution of IDW along with strategies to extend infrastructure lifespans and enhance demolition waste recycling. Finally, Section 5 encapsulates the principal findings.

2. IDW assessment model

To examine the sources and distribution of demolition waste generated during infrastructure development in China, we develop a provincial IDW assessment model based on the MFA method, as presented in Fig. 1. This model encompasses a diverse array of infrastructure types, including expressways, ordinary highways, urban roads, railways, subways, and pipelines for water supply, sewage, heat supply, and gas. It also accounts for key construction materials such as steel, copper, aluminum, cement, sand, gravel, asphalt, and plastics. Using this model, we comprehensively investigate the evolution of provincial infrastructure and its associated demolition waste from 1949 to 2100 under different Shared Socioeconomic Pathways (SSPs). Additionally, we assess various scenarios related to infrastructure lifespans and material recycling rates to explore the dynamic flow patterns of IDW. This analysis provides valuable insights for long-term infrastructure planning and supports the adoption of sustainable construction practices.

The provincial IDW assessment model primarily utilizes logistic curve modeling for various infrastructure stock types, integrating key driving factors, data compilation, and stock-driven MFA calculations. For the calculation of specific demolition waste, the volume of waste materials is determined by the extent of demolished infrastructure and the material intensity associated with each infrastructure type, as illustrated in Eq. (1).

$$MD_{i,j,t}^{k} = D_{i,t}^{k} \times MI_{i,t} \tag{1}$$

where $MD_{i,j,t}^{k}$ represents demolition waste material j from infrastructure i in province k at year t; The infrastructure i in province k that was demolished at year t is denoted by $D_{i,t}^{k}$; $MI_{i,t}$ represents the material intensity associated with infrastructure i at year t.

Building on the core principles of the MFA method, both demolished and newly constructed infrastructure are iteratively calculated alongside the growth of infrastructure stocks, as outlined in Eq. (2) and Eq. (3). Infrastructure stock growth is modeled using a logistic curve framework that incorporates key socioeconomic parameters, such as per capita GDP and population density (Dai and Yue, 2023; Huang et al., 2017). The logistic model for various infrastructure types is carefully developed for 31 provinces in China, with saturation levels, initial conditions, and growth patterns derived from historical infrastructure data, development plans, and benchmarks from developed countries.

$$D_{i,t}^{k} = \sum_{t'=t_0}^{t-1} L_i(t,t') \times N_{i,t}^{k} \tag{2}$$

$$N_{i,t}^{k} = S_{i,t}^{k} - S_{i,t-1}^{k} + D_{i,t}^{k} \tag{3}$$

where $N_{i,t}^{k}$ stands for the freshly built infrastructure i in province k at year t; $L_i(t, t')$ mirrors the likelihood that the infrastructure i built in year t' is dismantled at year t; $S_{i,t}^{k}$ represents the infrastructure stock i in province k at year t.

For infrastructure demolition, the service lifetime of infrastructure is typically assumed to follow a normal distribution, a method widely used in current research (Miatto et al., 2017).

$$L_i(t,t') = \left(1 \Big/ \sigma_i\sqrt{2\pi}\right) \times \exp\left(-(t-t'-\tau_i) \Big/ 2\sigma_i^2\right) \tag{4}$$

where τ_i and σ_i are the average lifetimes and standard deviation of the infrastructure i, respectively.

In our model, the material recycling rate serves as a key indicator for assessing the potential to recycle and utilize demolition waste. The material demands for newly constructed infrastructure are calculated using Eq.(5).

$$MN_{i,j,t}^{k} = N_{i,t}^{k} \times MI_{i,t} - R_{j,t} \times MD_{i,j,t}^{k} \tag{5}$$

where $MN_{i,j,t}^{k}$ denotes the emergent demand for material j that is linked to the newly established infrastructure i in province k at year t; $R_{j,t}$ denotes the recycling rate of material j at year t.

3. Data sources

Historical data on population, GDP, and land area from 1949 to 2022 are sourced from China's compendium of statistics (1949–2008) and China's statistical yearbook (1978–2022). Projections for these parameters from 2023 to 2100, estimated by Jiang et al. (2024) under various SSPs scenarios, are incorporated into the projection component of the provincial IDW assessment model, with the "middle of the road" scenario serving as the baseline. Additionally, historical data on the lengths of various infrastructure types, including expressways, highways, urban roads, railways, urban rail systems, and water supply, sewage, heat supply, and gas pipelines across 31 provinces from 1949 to 2022 were compiled from China Statistical Yearbook for the Regional Economy (1978–2022), China Urban-Rural Construction Statistical Yearbook (1978–2022), and the respective statistical yearbooks of 31 provinces (1978–2022).

3.1. The saturation level of various types of infrastructure across different provinces

Regarding infrastructure development, we assume that the length of various infrastructure types per unit area and per capita in China will eventually align with levels observed in developed countries (Huang et al., 2013). Specifically, based on provincial development plans, it is expected that the saturation levels in Beijing, Tianjin, and Shanghai will approach those of internationally developed cities. Meanwhile, infrastructure saturation levels in economically advanced provinces, including Guangdong, Jiangsu, Zhejiang, and Shandong, are anticipated to reach or even exceed those of developed countries in the foreseeable future. Infrastructure development in other provinces is projected to follow a similar trajectory, growing in tandem with these leading regions (Liu et al., 2021; Zhang et al., 2023). Detailed information on the saturation levels of various infrastructure types in developed cities and countries, as well as the development plans and saturation levels for the 31 provinces, is provided in Table S2–S8 in Supplementary Materials.

3.2. Lifetime

The lifespan of various types of infrastructure determines the scheduling of demolition activities, which in turn substantially affects IDW generation. As socioeconomic development progresses, it is anticipated that the average infrastructure lifespan will extend, ultimately aligning with levels observed in developed countries (Deetman et al., 2020). Drawing on existing design codes, standards, and relevant literature, it is possible to ascertain the average service lifespans of various types of infrastructure in China over different time periods. However, the average service lifespan is also influenced by construction practices and specific operating conditions in each province (Pei et al., 2024). Consequently, provincial-level disparities in infrastructure lifespan are anticipated, with consideration given to infrastructure service life under short, medium, and long categories, as detailed in the Supplementary Materials. Additionally, the standard deviation for lifespans of various infrastructure types is set to 30 % of the average lifespan within the lifespan distribution function (Mohammed et al., 2024).

3.3. Material intensity

China's infrastructure relies on a diverse range of materials, and the material intensity of various infrastructure types has been systematically compiled and organized by Li et al. (2023). Building upon this foundation, the impacts of climatic conditions and usage scenarios on regional variations are discussed in Supplementary Materials.

3.4. Material recycling potential

Recycling waste materials offers a viable strategy for reducing the extraction of natural resources, mitigating environmental pollution, and promoting resource reuse. Utilizing a comprehensive inventory of materials employed in various infrastructure systems, scenarios with both low- and high-growth recycling rates have been established to assess the state of waste recycling and utilization (see Table 1). These scenarios, based on relevant research and official reports, provide a prospective evaluation of the potential trajectory of IDW.

4. Results and discussion

In this section, we examine the evolution trends and spatial-temporal distribution characteristics of IDW. Furthermore, we investigate the potential for material metabolism through waste material recycling in the context of sustainable development. Finally, the dynamic flow trajectories of IDW are explored under diversified socioeconomic development scenarios.

Table 1
Recycling rate of materials in China by type.

Type of material	Current recycling rate	Growth rate (every five years)		Maximum recycling rate	References
		Low	High		
Steel	20 %	3 %	5 %	90 %	(Gao et al., 2025; Jia et al., 2021)
Copper	50 %	1 %	3 %	90 %	(Li et al., 2024; Wang et al., 2019)
Aluminum	20 %	1 %	5 %	90 %	(Dai et al., 2019; Yang et al., 2024)
Cement	0 %	1 %	3 %	\	(Shivaprasad et al., 2024)
Sand	10 %	3 %	5 %	90 %	(Gao et al., 2020; Zhang et al., 2020)
Gravel	10 %	3 %	5 %	90 %	(Gao et al., 2020; Zhang et al., 2020)
Asphalt	30 %	1 %	5 %	90 %	(Gao et al., 2022; Santolini et al., 2024)
Plastic	30 %	1 %	3 %	90 %	(Lase et al., 2023; Luan et al., 2021)

4.1. An overview of infrastructure demolition waste in China

The total length of demolished infrastructure has grown rapidly since 2000, as evidenced by the variation among different categories of demolished infrastructure in Fig. 2. This growth is projected to gradually slow after 2030, ultimately peaking at 730,788 km by 2050. Subsequently, the total demolished infrastructure is expected to decline, accompanied by fluctuations stemming from a maturing infrastructure stock and extended infrastructure lifespans.

Regarding specific demolition activities, the length of demolished ordinary highways is expected to peak in 2050 due to their relatively short service life. This trend will be followed by a sharp decline around 2070, driven by an increase in service lifespan, and then a subsequent rise due to accumulated construction activities. In contrast, expressways, urban roads, railways, heat supply pipelines, and gas pipelines, which generally have longer lifespans, are projected to reach their demolition peaks around 2060. Demolition of expressways and urban roads is expected to decrease by 2070, while demolition of railways, heat supply pipelines, and gas pipelines will decline by 2080. Water supply and sewage pipelines, with even longer lifespans, are expected to peak in 2070 and continue to decline through 2100. Meanwhile, urban rail demolition is projected to increase steadily until 2100. These observations suggest that prolonging infrastructure service life can reduce demolition waste production and facilitate the gradual decommissioning of different infrastructure types, thereby alleviating the immediate demand for natural resources.

As critical components of the overall infrastructure network, ordinary highways considerably shape these demolition trends, contributing to the notable decrease in demolished infrastructure in 2070, as shown in Fig. 2(a). In general, demolished ordinary highways constitute 44.98 %–87.79 % of all infrastructure demolition during the 1949–2100 period. Additionally, since 2020, more than 19,312 km of pipelines have faced aging and safety risks annually, culminating in a potential peak of 210,121 km in total pipeline demolition length.

The evolution trends of IDW are illustrated in Fig. 3(a). A notable rise in IDW is projected, increasing from 110.20 Mt in 2000 to a peak of 838.15 Mt by 2050, marking a 2.36-fold increase compared to 2020. Demolition waste generated from various infrastructure types is primarily composed of sand and gravel, which together account for over 87 % of the total IDW, followed by cement, which makes up nearly 10 %. Specifically, the quantities of sand, gravel, and cement found primarily in ordinary highways, railways, and water supply and sewage pipelines are expected to increase from 122.69 Mt, 190.82 Mt, and 36.44 Mt in 2020, respectively, to 293.35 Mt, 444.57 Mt, and 80.37 Mt by 2050. This will be followed by a decline around 2070 due to the reduction in ordinary highway demolition. Waste steel, a key construction material, accounts for about 2 % of IDW across all infrastructure types. It is expected to peak at 15.59 Mt in 2060 before gradually declining and then rising again after 2080. Similarly, copper waste, largely driven by urban road and pipeline demolition, follows a pattern similar to steel. Aluminum and asphalt waste, primarily linked to ordinary highways, are expected to peak at 0.74 Mt and 5.10 Mt, respectively, by 2050. Finally, plastic waste, mostly generated from water supply and sewage pipelines, will gradually decline after reaching a peak of 0.79 Mt in 2070.

4.2. Spatial-temporal distribution characteristics of IDW

The substantial disparities in socioeconomic development, climatic conditions, and geographical characteristics across China's provinces considerably influence the growth of various types of infrastructure,

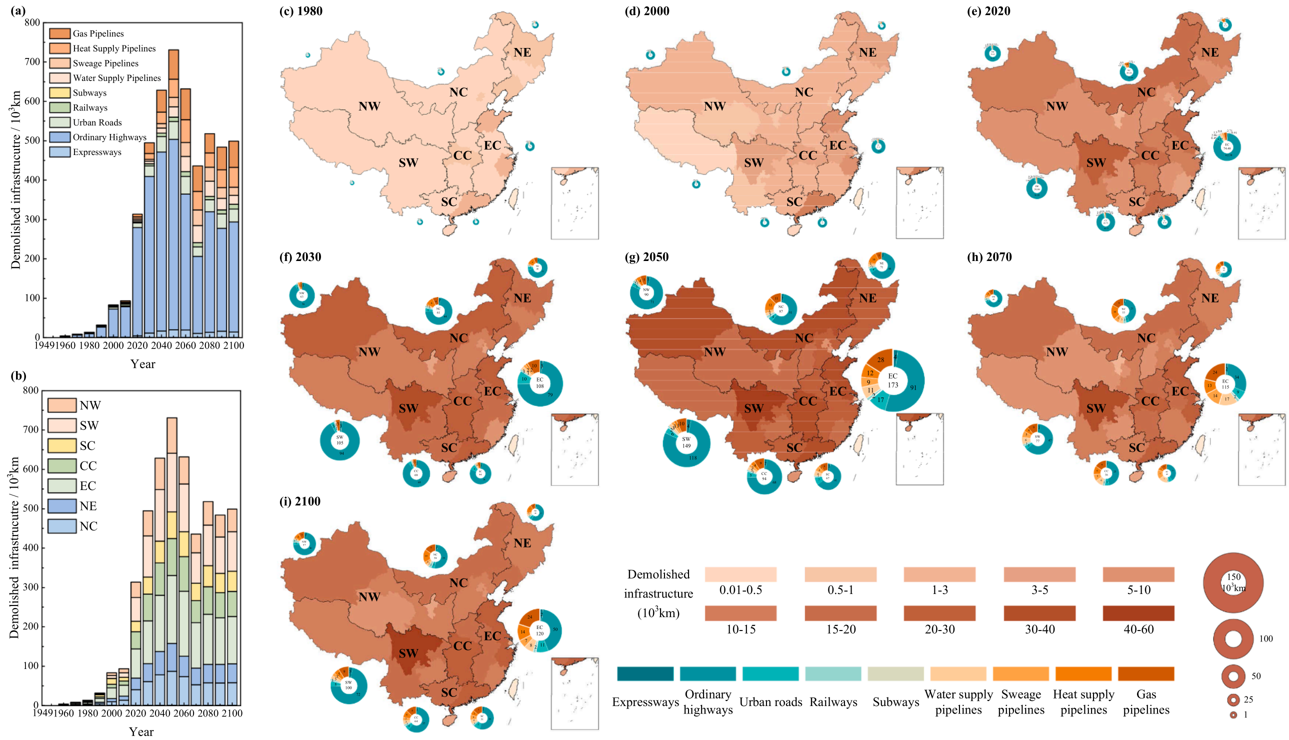

Fig. 2. Spatial-temporal distribution characteristics of demolished infrastructure in China. **a**. Distribution of total demolished infrastructure by infrastructure type; **b**. Distribution of total demolished infrastructure by region; **c-i**. Spatial distribution of demolished infrastructure in China from 1949 to 2100. The varying shades of brown on the maps illustrate changes in the total length of demolished infrastructure across provincial networks. The pie charts represent different types of infrastructure, with the numerical values indicating the length of demolished infrastructure. The size of each pie chart is directly proportional to the length of the demolished infrastructure. The regions are labeled as follows: Northeast China (NE), North China (NC), Northwest China (NW), East China (EC), South China (SC), Central China (CC), and Southwest (SW).

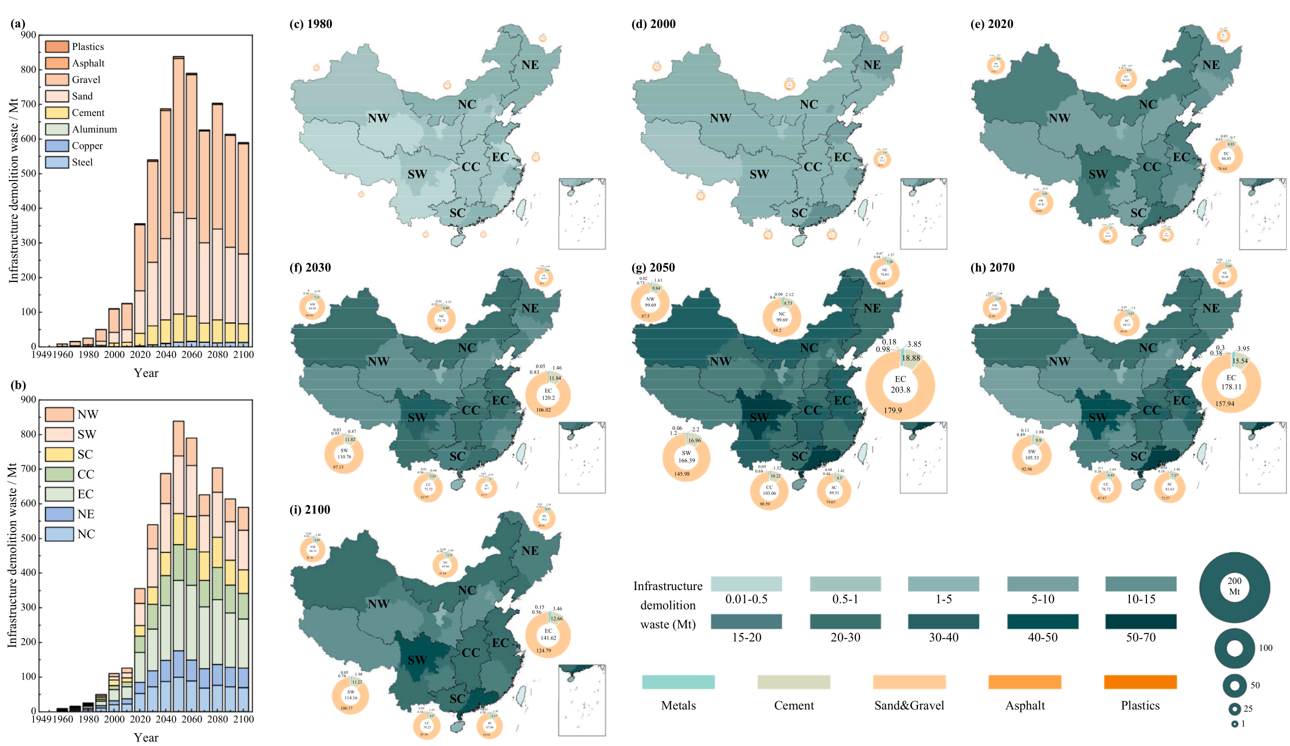

Fig. 3. Spatial-temporal distribution characteristics of IDW in China. **a**. Distribution of total IDW by infrastructure type; **b**. Distribution of total IDW by region; **c-i**. Spatial distribution of IDW in China from 1949 to 2100. The varying shades of green on the maps depict changes in IDW across provincial infrastructure networks. The pie charts represent different material types, while the numbers indicate the quantity of specific demolition waste elements. The size of the pie charts is proportional to the amount of IDW.

which in turn impacts the generation and distribution of IDW. To analyze the dynamic variations in provincial IDW, this study examines the spatial-temporal distribution of demolished infrastructure and demolition waste materials, as presented in Fig. 2(c)-(i) and Fig. 3(c)-(i), respectively.

In terms of the spatial-temporal distribution of demolished infrastructure, provinces in East China (EC), Central China (CC), South China (SC), and Southwest China (SW) have consistently ranked among the top ten in overall demolished infrastructure length since 2000. Notably, Sichuan, Shandong, and Guangdong exhibit the highest demolition volumes, with projections indicating that each could exceed 35,000 km by 2050. In contrast, Liaoning and Heilongjiang in Northeast China (NE), as well as Hebei and Shanxi in North China (NC), have dropped from relatively leading positions after 2000 to mid- and low-tier rankings at the national level. Although initiatives such as northeast revitalization and western development have been implemented, infrastructure development in most northern provinces, particularly those in NE and Northwest China (NW), continue to lag behind that of southern regions. Inner Mongolia and Xinjiang serve as distinctive examples with shorter infrastructure lifespans and extensive road and pipeline requirements, suggesting that the length of demolished infrastructure in these areas may surpass 20,000 km by 2030 and 30,000 km by 2050. By contrast, Ningxia, Hainan, Shanghai, Beijing, and Tianjin have documented the least demolished infrastructure length since 2020.

The spatial distribution of demolished infrastructure further amplifies the north-south disparity in IDW, primarily due to the considerable scale of water supply pipeline demolition in densely populated areas and the extensive demolition of sewage pipelines in regions with high precipitation. These regions also exhibit a relatively higher demand for construction materials for both water supply and sewage pipelines. Collectively, Guangdong, Sichuan, and Shandong account for 15.49 %–24.25 % of China's total IDW from 1949 to 2100. In 2020, waste in these provinces reached 15 Mt, with projections suggesting it will exceed 35 Mt by 2050. In contrast, Ningxia, Hainan, Beijing, Shanghai, and Tianjin produce the lowest levels of IDW, with annual peaks under 15 Mt. Consequently, there is an urgent need for comprehensive tracking, screening, and recycling measures to efficiently manage the rapidly increasing IDW generated from diverse infrastructure sources.

4.3. IDW recycling potential for infrastructure material metabolism

According to circular economy principles, recycling demolition waste holds great potential for reducing environmental pollution and minimizing the demand for natural resources, thereby contributing effectively to material metabolism. Although China has achieved a preliminary level of waste material recycling, the quality of recycled materials often falls short of construction standards, particularly for high-demand infrastructure sectors like transportation and pipelines (Pauliuk et al., 2012). In this research, we examine both low- and high-growth material recycling rates to assess the potential for recycling IDW relative to the current recycling levels. The resulting potential for national-level material recycling is shown in Fig. 4, and the corresponding provincial-level findings are provided in Supplementary Data. In addition, the final demand for various materials, categorized by infrastructure type, is compared with the available supply of recycled scrap, as illustrated in Fig. 4.

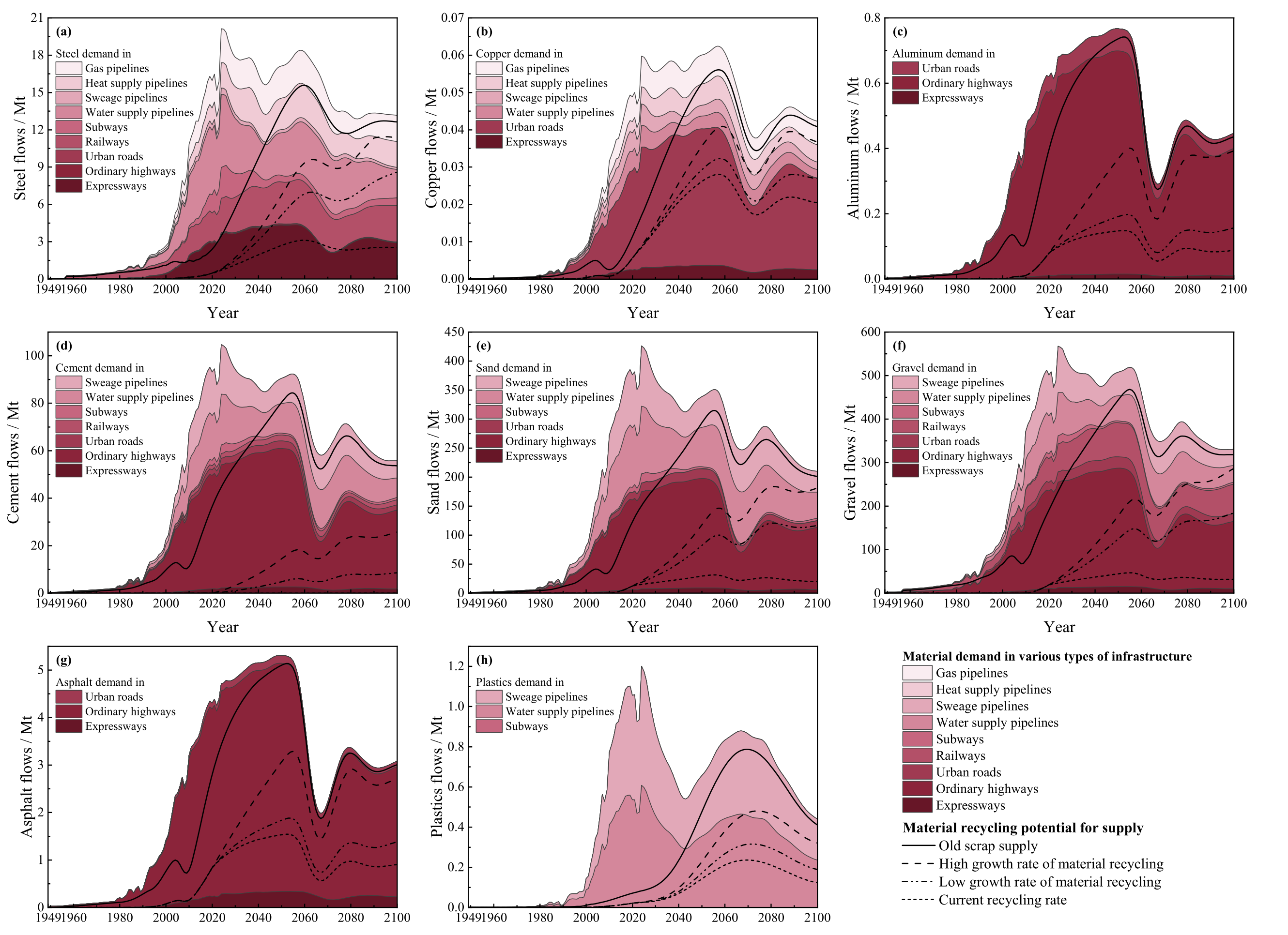

Fig. 4. Material recycling potential for future infrastructure construction. **a.** Steel; **b.** Copper; **c.** Aluminum; **d.** Cement; **e.** Sand; **f.** Gravel; **g.** Asphalt; **h.** Plastics.

Regarding specific materials, the amount of demolition waste comprising steel, copper, cement, sand, gravel, and plastics is projected to align closely with the demands for new infrastructure construction at the national level by around 2060. The recycling potential for aluminum and asphalt is expected to become viable as early as 2040. By this time, concerns regarding the availability of old scrap will have diminished, though maintaining the strength, durability, and performance of recycled materials will remain a new challenge. Compared with the national potential for demolition waste recycling, provinces with more advanced infrastructure networks, including Beijing, Shanghai, Tianjin, Jiangsu, Zhejiang, Guangdong, and Shandong, could achieve infrastructure material metabolism 10 to 20 years earlier than the national trajectory, with other provinces following the national pattern.

Currently, the recycling capacity of steel in secondary production stands at approximately 20 % (Jia et al., 2021). However, the substantial volume of waste steel highlights the need for stricter recycling standards, wider adoption of technologies such as electric arc furnaces, and more rigorous enforcement of steel recycling policies. These measures could substantially enhance the recycling of steel materials derived from IDW. If a 60 % recycling rate is attained by 2060 (Gao et al., 2025), approximately 9.35 Mt of scrap steel can be recovered, fulfilling 51.25 % of the projected steel demand for infrastructure construction.

Due to the relatively short lifespans of ordinary highways, the quantities of aluminum and asphalt waste are expected to increase rapidly over the next decade. However, with aluminum recycling at 20 % (Dai et al., 2019) and asphalt recycling at 30 % (Gao et al., 2022), meeting future demand for these materials presents a challenge. Implementing widespread secondary aluminum production (Yang et al., 2024) and reclaimed asphalt pavement (Santolini et al., 2024) technologies could substantially reduce waste generation while addressing a substantial portion of the future demand for aluminum and asphalt. With respect to plastics, the current recycling rate stands at 30 % (Luan et al., 2021), and recycled plastics currently account for only 2.02 % of the total demand for plastics in infrastructure construction. Therefore, it is crucial to promote both mechanical and chemical recycling techniques to enhance plastic circularity. If the recycling rate for plastics reaches approximately 54 % by 2060 (Lase et al., 2023), it would enable the recycling of 0.38 Mt of scrap plastics, essentially meeting the demand for plastics in water supply pipeline construction. Similarly, maintaining a copper recycling ratio of 50 % and gradually increasing the proportion of recycled copper (Wang et al., 2019) is expected to meet 67.25 % of copper demand for infrastructure construction.

The predominant component of IDW is discarded concrete, typically consisting of waste cement, sand, and gravel. This material can be processed through crushing and screening to produce recycled aggregate, thereby providing alternative sources of sand and gravel. Given that construction and demolition waste in China is currently recycled at a rate of only 10 % (Gao et al., 2020), enhanced recycling and utilization of waste concrete could help alleviate the ongoing sand crisis and reduce carbon emissions (Zhong et al., 2022). In particular, the application of advanced dry recovery technology in combination with a heating-air classification system (Shivaprasad et al., 2024) not only yields recycled aggregate that can satisfy a substantial portion of the demand for sand and gravel but also produces cementitious particles that may substitute for cement. This approach can considerably reduce CO_2 emissions associated with traditional cement production processes.

4.4. *Dynamic flow trajectory of IDW under various scenarios*

In response to advancements in infrastructure construction and IDW recycling technologies, shaped by varying socioeconomic development and policy mandates, we further investigate the multi-scenario evolution of IDW under different SSPs. The analysis explores the implications of long, medium, and short infrastructure lifespans, as well as high and low material recycling rates, with national IDW flow trajectories illustrated in Fig. 5. Results indicate that IDW generation could peak at approximately 317.43–1084.72 Mt by 2050. Subsequently, as infrastructure stocks reach saturation, infrastructure lifespans extend, and waste materials recycling rates improve, a notable decline in IDW is projected, potentially reducing generation to 59.72–393.12 Mt by 2100.

To further examine the impacts of extending infrastructure lifespans and enhancing recycling rates, and to devise more comprehensive strategies for IDW management and utilization, this study assesses these factors under a "middle of the road" pathway. Compared to a baseline

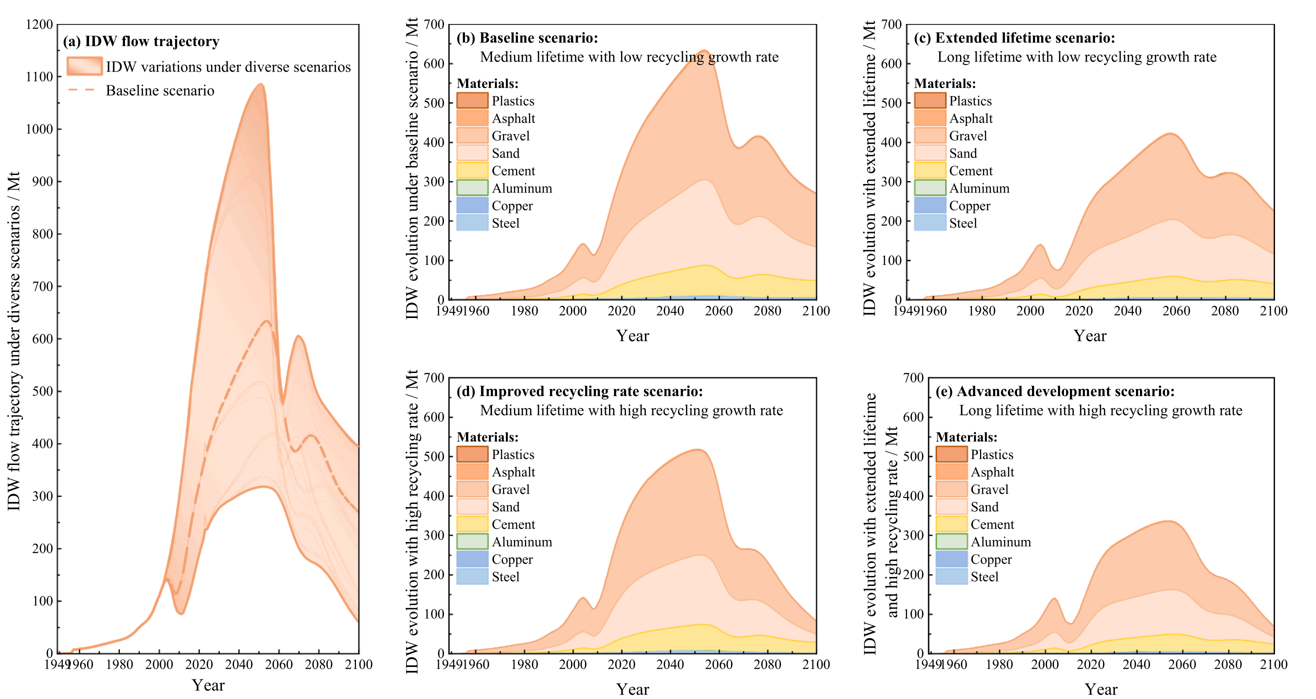

Fig. 5. Dynamic IDW evolution under diverse scenarios. **a.** IDW trajectories under different SSPs, infrastructure lifetime, and material recycling rates; **b.** Baseline scenario; **c.** Extended lifetime scenario; **d.** Improved recycling rate scenario; **e.** Advanced development scenario.

scenario, assuming a medium infrastructure lifespan and low recycling rate, prolonging the lifespan of infrastructure is expected to reduce IDW by 35.54 % in 2050. This represents a 22.93 % decrease relative to a scenario focusing solely on improving recycling rates. However, as the infrastructure network continues to expand, the effectiveness of lifespan extension in mitigating IDW generation gradually diminishes. In contrast, higher recycling rates notably enhance the effective utilization of urban mining resources and contribute to the realization of circular resource metabolism. When both strategies are implemented simultaneously, IDW generation is projected to decrease by 46.07 % in 2050 and by 74.64 % in 2100. This synergistic approach not only substantially curbs IDW generation in the coming decades but also promotes the long-term sustainable development of infrastructure networks.

Given the ongoing rise in IDW, it is imperative for the government to implement targeted incentive policies that enhance material recycling and improve the overall IDW management framework, with a particular focus on sand, gravel, and cement. Furthermore, promoting technological innovation in infrastructure construction is essential to extend infrastructure lifespans and reduce waste generation at its source. From an industry standpoint, deconstruction and demolition teams should prioritize worker training to develop specialized expertise and adopt emerging technologies, such as robotics, to facilitate efficient demolition and on-site segregation of IDW for subsequent recycling. Simultaneously, material manufacturers should aim to increase the proportion of waste materials in their production processes. Contractors are encouraged to progressively incorporate materials derived from recycled waste into their projects, thereby fostering a more sustainable construction industry.

5. Conclusion and outlook

This study develops an IDW assessment model to analyze demolition waste generated from the provincial infrastructure network. It examines the evolutionary trends and the spatial-temporal distribution characteristics of demolition waste across different categories of infrastructure. Additionally, the material recycling potential and multi-scenario evolution are explored. The primary conclusions are summarized as follows:

(1) The distribution of IDW reveals pronounced regional imbalances between southern and northern provinces in China. Particularly, provinces in NE and NW regions generate less IDW compared to those in the EC, CC, SC and SW regions. From 1949 to 2100, the annual total IDW generated by Guangdong, Sichuan, and Shandong contributed 15.49 %–24.25 % of the national total.
(2) The recycling potential for materials such as steel, copper, cement, sand, gravel, and plastics is expected to meet the demands of future infrastructure construction at a national scale by 2060, while aluminum and asphalt are projected to achieve this by 2040. Regions such as Beijing, Shanghai, Tianjin, Jiangsu, Zhejiang, Guangdong, and Shandong are expected to reach material metabolism capabilities 10–20 years earlier than other provinces, aligning with the national trend.
(3) IDW is projected to escalate substantially, rising from 110.20 Mt in 2000 to a peak range of 317.43–1084.72 Mt by 2050, followed by a fluctuating decline to 59.72–393.12 Mt by 2100 due to saturation of infrastructure stock. Importantly, strategies to extend infrastructure lifespan and enhance material recycling rates are projected to reduce IDW generation by 46.07 % in 2050 and by 74.64 % in 2100.

Building on the insights gained from material demolition management, particularly regarding IDW dynamics and recycling potential, several tailored recommendations are proposed. First, improving the recycling rates of waste materials is a crucial step toward maximizing resource utilization and mitigating environmental pollution. This will help close the loop on material flows, reducing the need for virgin materials and minimizing waste generation. Second, advancing infrastructure construction technologies to extend the lifespan of existing structures is an essential strategy for reducing IDW generation at its source in the coming decades. By enhancing the durability of infrastructure, the frequency of demolition and material waste can be substantially lowered. Finally, since cement, sand, and gravel are the primary components of IDW and currently have low recycling rates in China, prioritizing the development of recycling and utilization technologies for these materials is vital to reducing IDW. Enhancing their recycling potential will play a key role in promoting sustainable material metabolism and decreasing the environmental footprint of construction activities.

This research also includes a comprehensive uncertainty analysis to evaluate the robustness of the findings, particularly concerning logistic model parameters related to saturation levels and growth patterns. Detailed results of the uncertainty analysis are provided in the Supplementary Materials, while provincial results are included in Supplementary Data. Furthermore, as IDW recycling involves diverse stakeholders, such as government entities and enterprises, and entails various costs associated with implementing technical measures, future studies should incorporate comprehensive cost-benefit analyses and foster multi-stakeholder negotiations to promote cooperative management within the demolition waste recycling market.

CRediT authorship contribution statement

Bao-Jun Tang: Writing – original draft, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Yu Yuan:** Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis. **Yangyang Guo:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Ying Zou:** Writing – review & editing, Methodology. **Huchen Feng:** Writing – review & editing, Investigation.

Declaration of competing interest

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

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2025.108272.

Data availability

The data supporting the findings of this study are available and provided in Supplementary Data.

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