Estimation and Projection of Construction and Demolition Waste Generation in Beijing Using Empirical Construction Data

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Abstract
Rapid urban growth generates unmanageable volumes of construction and demolition (CDW) waste in cities worldwide, necessitating reliable quantification of current and future waste trends to inform policy. Using empirical data and a straightforward methodology suited to data-scarce regions, this study estimated Beijing's CDW output from 2008 to 2022. CDW generation rates reflecting material losses and demolition processes were multiplied by construction/demolition areas to quantify waste. Results reveal over a 4-fold increase in CDW from 31 million tons in 2008 to 52 million tons in 2022. Concrete, brick and mortar comprised 85% of waste composition. Construction waste accounted for a larger proportion recently, totaling 57% over the 15-year analysis period. Using a -1% construction area growth rate and 40% project completion rate, CDW generation was forecast to reach 55 million tons by 2033. The exponential rise, outpacing utilization capacity, underlines the urgent need for CDW minimization, recycling and sustainable management aligned with circular economy principles in Beijing and similarly developing cities. Although omitted excavation waste contributes uncertainty, the scalable quantification methodology could help developing cities plan waste facilities and policies. While projected CDW growth rates may primarily reflect wider construction sector changes rather than climate policies, lack of linkage with economy-wide decarbonization trajectories highlights an area needing more research. By generating new insights plus an adaptable city-level waste modeling approach, this exploratory study provides a foundation for subsequent work to track on-site audits, connect localized data to carbon budgets, and realize ambitious reuse targets.

Keywords: construction and demolition waste, circular economy, environmental impact, renovation waste

INTRODUCTION

Construction demolition and renovation waste (CDW) has become a major environmental challenge associated with rapid urbanization worldwide. The waste composition is predominantly mixed concretes, bricks, wood, plastics, metals and other construction materials [1],[2],[3],[4]. As cities continue to grow at unprecedented rates, the development and demolition of buildings and infrastructure generates massive volumes of waste [3],[5]. In the United States of America, about 600 million tons of CDW was generated in 2018 and 90% of the total waste came from demolition activities. Approximately 455 million tons of C&D material were directed to next use, while around 145 million tons were disposed of in landfills [6]. About 450-500 million tons of CDW are generated every year in the EU [7]. In China alone, over 2 billion tons of CDW is produced annually, constituting about 30-40% of total municipal solid waste. Recycling rate of CDW in China is far less than the rate of many developed countries. In China, the overall recycling and disposal rate for CDW is less than 40%, with the majority of Chinese cities still employing landfilling [2]. This poses environmental and economic challenges associated with landfill, including pollution, health hazards from contaminated sites, and the depletion of landfill capacity, ultimately burdening the environment and its inhabitants [4],[8]. Therefore, sustainable management of CDW through the promotion of a Circular Economy (reduce, reuse, and recycle) has become a pressing priority in cities throughout China [2, 5]. However, a critical initial step toward achieving sustainable CDW management is the accurate quantification of waste to understand its sources, volumes, and trends.

Several approaches have been used for the classification, quantification and estimation of CDW as illustrated in Table 1. These approaches include: site visit (SV) or field monitoring, materials flow analysis (MFA), geographic information system (GIS), waste generation rate (WGR) calculation method and etc. The site visitation method, which involves direct on-location auditing and quantification of waste streams, provides valuable in situ data on factors influencing CDW generation. As Poon et al. [9] demonstrated through site visits in Hong Kong, rigorous on-site waste management practices enabled public housing projects to achieve low waste rates of 3.2%, far below private builds. First-hand observation of construction processes and waste outputs via site visitation can thus give deeper insight into relationships between on-site waste behaviors and overall waste minimization. For understanding waste in the context of a city's construction boom, an embedded site visitation methodology would be highly beneficial. Direct, frequent site assessments across a representative sample of projects could quantify waste rates, composition, and variability. As applied in previous studies, on-site measurements can be supplemented by interviews, surveys, and documentation to give a detailed profile of waste generation patterns [10]. By embedding site visitation within a larger study, both localized insights and wider city-level waste generation models can be produced through integrated analysis of first-hand observational data. This mixed-methods integration of site-based waste audits with larger-scale estimation techniques is recommended for robust CDW analysis [11].

Several studies have also employed Material Flow Analysis (MFA) to analyze the flow of waste materials within the construction industry and identify potential areas for waste reduction and recycling. Guo and Huang, 2019 [12] highlights the importance of MFA in analyzing CDW management and identifies research gaps and future directions for its development. In the USA, Cochran and Townsend (2010) [13] used MFA to analyze the flow of construction and demolition (C&D) waste in Florida, providing insights into the sources and destinations of waste materials and identifying opportunities for waste reduction and recycling. In South Africa, Berge & Von Blottnitz [14] estimated construction and demolition waste quantities and composition, highlighting that CDW quantities in South Africa appear to be considerably under-reported. Abdelshafy and Walther [15] introduces a Dynamic-Locational MFA model that integrates spatial, temporal, and material characteristics to analyze the development of urban stock and reconcile supply and demand of materials. These studies demonstrate the usefulness of MFA in estimating CDW generation and developing strategies for waste reduction and recycling in the construction industry.

Geographic Information System (GIS) is a powerful tool that has been employed in various studies to analyze and manage construction and demolition (C&D) waste generation. GIS allows researchers to visualize, analyze, and interpret spatial data to reveal patterns, relationships, and trends in CDW management. In a study conducted in Shenzhen city, China, Wu et al., [16] proposed an innovative approach to managing demolition waste using GIS, which helped in quantifying the demolition waste from generation to final disposal. He proposed a GIS-based model to quantify and manage demolition waste, highlighting the potential economic benefits of recycling. Another study by Paz et al., [17] presents a case study in Brazil where GIS tools were used to map illegal waste dumping sites, assess environmental risks, and identify suitable locations for CDW management facilities. The integration of GIS in CDW management research has proven to be valuable in identifying waste generation patterns, optimizing waste disposal strategies, and promoting sustainable waste management practices. The waste generation rate (WGR) calculation method has been employed in numerous of studies. The initial step is to determine the amount of construction, renovation, and demolition activities. Finding the precise waste generation rate associated with each type of activity is the second step. The final step involves estimating the total CDW generation (i.e., multiplying the floor area by the waste generation rate, kg/year or tons/year). Ding and Xiao [18] estimate that approximately 13.71 million tons of CDW waste was generated in Shanghai in 2012, with concrete, bricks, and blocks being the main components.

Coelho and de Brito [19] present a methodology to quantify CDW generation in Portugal and predicts an increase in the future. Qiao et al. [20] combined the waste generation rate calculation method and exponential smoothing method to subsequently analyze the output of CDW in Shandong Province and predicts its future growth.

While several CDW waste estimation techniques exist, each has limitations in terms of data requirements, cost, and applicability for different project types. For example, the site visit method provides only a snapshot of waste generation and lacks representativeness across projects [10]. Material flow analysis involves extensive data collection on material inventories and unverified assumptions about waste conversion ratios, posing feasibility constraints [21],[22],[23]. Geographic information system modeling requires significant technical expertise along with large amounts of accurate spatial data, which poses adoption barriers [16]. Despite its inability to estimate the amount of waste generated from hazardous materials or specialized equipment, the WGR method remains a useful and effective method for estimating the amount of CDW generated. By collecting accurate and representative data on waste generation and accounting for any factors that may affect waste generation, it is possible to develop WGRs that reflect the specific characteristics of the project or region and make informed decisions about waste management strategies [24],[11].

Beijing, the capital of the most populous nation in the world, has witnessed extensive construction and demolition activities driven by rapid economic growth and urban expansion. The urban built-up area in Beijing is expanding, while farmland is steadily dwindling. In 2015, approximately 29 km² of farmland was lost annually due to urban expansion [25]. This urban sprawl, accompanied by significant building infrastructure expansion, renovation, and demolition, has led to a substantial increase in CDW generation. Unfortunately, a significant portion of this waste is disposed in landfills, with only a fraction being recycled or reused. This situation is exacerbated by the absence of a unified and up-to-date data on the generation of CDW presently. Due to the lack of statistical information on the generation of Construction waste, demolition waste, and renovation waste in Beijing over the years, it is not possible to directly model and predict from the perspective of time series of Construction waste generation, nor is it suitable to use other prediction methods that directly establish series relationship of prediction models based on Construction waste generation over the years.

Therefore, this study aims to estimate and predict the CDW output of Beijing using the waste generation rate calculation (WGR) method. Reliable CDW estimation is foundational for informing management policies and assessing their efficacy. Hence, the current study aims to help fill this research gap by devising an innovative CDW quantification methodology tailored to Beijing and evaluating its performance using empirical data

Table 1 Methodologies and findings of relevant literature reviewed for this study.

Methodology	Year	Waste type	Region	Key findings	Reference
SV and surveys	2022	CDW	Kuwait	Kuwait generates 49.5 kg/m^2 construction and demolition waste, with 54% of projects disposing of it in landfills due to issues like reworks, poor material quality, and improper site management.	Almusawi et al. [26]
MFA and WRG	2022	CDW	South Africa	South Africa's CDW generation rate is significantly underreported, with only 10.8 Mt of potential waste reaching disposal facilities, highlighting the need for accurate measurement and reuse of waste.	Berge and Von Blottnitz [14]
MFA	2019	CDW	India	In 2016, Indian cities generated over 150 million tons of C&DW, with 50%	Jain et al. [27]

				in small to medium towns, highlighting potential for recycling and material loop closure.	
GIS	2016	CDW	Shenzhen, China	Between 2015 and 2060, the Nan Shan District is projected to generate 135 million tons of demolition waste.	Wu et al. [16]
GIS	2020	CDW,	Brazil	The research identifies optimal waste facility locations and quantifies environmental risks, emphasizing the need for integrated construction waste management through training, inspections, audits, and public education.	da Paz et al. [17]
GIS and MFA	2022	CDW	Xiamen, China	Building material in-use stock in Xiamen rose quickly, with an average annual growth rate of 11%, from 1.58 Mt in 1980 to 91.13 Mt in 2018.	Liu et al. [28]
WRG	2007	CDW	Florida, USA	In 2000, Florida produced 3,750,000 metric tons of building-related C&D debris, with concrete accounting for 56% of the total.	Cochran et al. [11]
SV	2011	CDW	Shenzhen, China	According to the study, the waste produced ranged from 3.275 to 8.791 kg/m^2, with concrete, wood for falsework and formwork, and other waste making up the majority of the waste.	Lu et al. [24]
WGR	2017	CDW	China	China produced 1.13 billion tons of CDW materials in 2014.	Lu et al. [4]
WGR and others	2020	CDW	Shandong, China	Shandong produces 110 million tons of C&D trash, and with annual growth of 3.07%, that number is projected to reach 140 million tons by 2025.	Qiao et al. [20]
WGR and others	2022	CDW	Jiangsu, China	CDW has increased dramatically from 16.2 million tons in 2000 to 233.23 million tons in 2020.	Liu et al. [29]
SV	2004	CDW	Hong Kong	Generation rates obtained for both projects were 0.4 m^3/m^2 and 0.65m^3/m^2	Poon et al. [9]
WGR and others	2011	CDW	Portugal	Estimated and predicted the CDW generation figure to be 415.7kg $person^{-1}$ $year^{-1}$ in 2020 considering the average value cited for European Union then.	Coelho and de Brito et al.[19]
WGR	2014	CDW	Shanghai, China	In 2012, Shanghai generated 13.71 million tons of CDW, with 80% being concrete, bricks, and blocks.	Ding and Xiao et al. [18]
MFA	2010	CDW	Beijing, China	In 2010, 35 million metric tons of C&D garbage were generated in Beijing, with significant growth expected in the future.	Hu et al. [30]

METHODOLOGY

Many studies have applied the waste generation rate (WGR) calculation methodology to estimate CDW output because it is simplified and data required for calculation are often available in national, regional or provincial statistical yearbooks [4],[6],[29],[18],[21],[31],[32]. These data are comparatively thorough and reliable [21, 32]. The WGR methodology determines CDW generation by multiplying the floor area (m^2/year) by the waste generation rate per unit area (kg/m^2 or $tons/m^2$). In this research, the WGR approach is used in conjunction with the acquired data to estimate CDW generation in Beijing, China. Equation (1) provides a straightforward explanation of this method.

$$CDW = C_w + D_w = (C_A \times WGR_C) + (D_A \times WGR_D) \tag{1}$$

where CDW is the total waste generated within a given year (million tons); C_W and D_W, are the construction waste and demolition waste, respectively (million tons). C_A and D_A, are the floorspace under construction and demolition area, respectively (m^2). Likewise, WGR_C and WGR_D are the waste generation rates of construction and demolition activities, ($tons/m^2$). However, data relating to demolition area and renovation/decoration area in Beijing are limited. In the absence of these statistical data, an alternative method is to estimate the areas. In this study, we assume that The annual demolition area is taken as 10% of the newly started construction area of that year. Similar concept is adopted in the Technical Assistance Consultant's Report of China on Construction and Demolition Waste Management and Recycling by The PRC Ministry of Housing and Urban-Rural Development and the Asian Development Bank [33].

Prediction

For prediction of the future generation of CDW in Beijing, we use geometric extrapolation in this study. The extrapolation corresponds to our assumption that the construction floorspace or area experiences constant growth due to construction activities (i.e., construction and demolition) and other economic factors and this growth is proportionate [34],[35]. The expected construction areas can be calculated by Equation (2) to determine the CDW generated for each year from 2023 until 2033. The rate of increase in construction floorspace can be determined by Equation (3).

$$F_i = F_0(1 + r) \tag{2}$$

$$r = \frac{F_0 - F_P}{F_P} \times 100 \tag{3}$$

where F_i is the expected floorspace (floorspace under construction or floorspace completed) for the specific year (m^2); F_0 represents current floorspace (floorspace under construction or floorspace completed); F_p is the floorspace of the previous year (floorspace under construction or floorspace completed); r the annual rate of growth (%). Once all of the above parameters are known, the expected demolition area (D_A) can be calculated using the assumptions made in the first part of the methodology.

Data Sources

In this study, data on construction areas (i.e., floorspace under construction and floorspace completed) as shown in Table 2 and Table 3 were obtained from the Beijing Statistical Yearbook [36] and the Achieve of the National Bureau of Statistics of China [37] for the period 2008 to 2022. The data on the demolition area were calculated based on the assumptions formulated after reviewing the relevant literature [4],[38],[33]. The construction area data from official statistics provides a useful indicator for estimating the amount of construction debris generated in Beijing during the study period. However, published statistics do not fully account for demolition activities, which also generate substantial amounts of waste.

RESULTS and ANALYSIS

Data collected and result calculation

Before estimating the total CDW, the construction and demolition floorspaces have to be known. For construction waste calculation of Beijing, the data C_A (m^2), can be obtained from The Beijing Statistical Year Book [36]. Unlike construction area, the data D_A (m^2) is calculated based on assumption made in the methodological section of this study. The data shown in Table 2 illustrates the floorspace of construction and demolition activities in Beijing for the past fifteen years, ranging from 2008 to 2022.

Table 2 Beijing Municipal floorspace data ranging from 2008-2022.

Year	Floorspace under construction (10,000 m^2)	Floorspace completed (10,000 m^2)	New construction area (10,000 m^2)	Demolition Area (10,000 m^2)
2008	19537.09	4803.00	19537	1953.70
2009	22720.64	5225.00	8409.00	840.90
2010	29440.40	5933.00	12652.00	1265.20
2011	36506.91	6456.00	13523.00	1352.30
2012	41660.34	8414.00	13567.00	1356.70
2013	49259.06	8950.00	16549.00	1654.90
2014	56477.12	9275.00	16493.00	1649.30
2015	59776.73	9886.00	13186.00	1318.60
2016	61097.53	10703.00	12024.00	1202.40
2017	65290.12	9844.00	14036.00	1403.60
2018	71969.30	9771.00	16450.00	1645.00
2019	80556.80	10937.00	19525.00	1952.50
2020	88593.70	9592.00	17629.00	1762.90
2021	91154.80	13255.00	15816.00	1581.60
2022	89888.27	13815.37	12548.67	1254.87

In terms of the construction waste generation rate (WGR_C), we estimated 0.0407 ton/m^2 based on the analysis of construction material losses in various types of buildings, including brick-concrete, frame, and cast-in-situ concrete structures [3]. This value was obtained through the application of concepts from the Handbook of Green Building Evaluation Standards (GBT 50378—2019) [39] published by the Chinese Ministry of Housing and Urban–Rural Development.

According to the amount of building materials per unit building area determined in the "Building Construction Manual" of China Construction Industry Press, the unit area generation coefficient of demolished construction waste for each structure type can be obtained, as detailed in the table below [40]. At present, in the process of renovating old cities in China, the proportions of three types of building structures: mixed, steel-concrete, brick-wood and steel are 45%, 30%, 20% and 5%.

The waste generation rate (WGR_D) of demolition activity was set based on values of earlier studies by Zhu et al.[41] and Chen et al. [42]. We apply rule of thumb and adopt the average of 1.197 ton/m^2 as the demolition waste generation rate. A study by Lu et al., [4] also employed similar method to estimate the demolition waste generation rate in his study.

Quantification of CDW

Beijing ranks sixth, just behind Jiangsu, Zhejiang, Guangdong, Shandong, and Hubei, in terms of floorspace under construction, according to data obtained from the Achieve of the National Bureau of Statistics of China [37] for the period covered by this study. Table 3 presents a comprehensive overview of the estimated generation of construction and demolition waste (CDW) associated with building-related activities in Beijing from the years 2008 to 2022. According to the results in the table below, the yearly output of C&D related waste in Beijing has surpassed 50 million tons in 2022. The accumulation of CDW over the past 15 years has reached 617 million tons, disregarding resources utilization. In 2015, CDW resource utilization rate reached 80% in Beijing by improving disposal capacity of facilities, as per the notice issued by the Beijing Municipal People's Government. However, waste generated from (1) construction of new buildings, demolition of old buildings, (2) relocation and renovation of municipal infrastructures (such as subway construction, overhead bridges, municipal pipelines renovation, etc), (3) decoration of residential buildings, and from (4) construction of structures that collapsed due to natural disaster or unexpected reason (such as heavy rainfall, typhoons, aging, etc) continue to increase. The average generation of CDW in Beijing is expected to remain around 40 million tons annually for the next few years.

Table 3 CDW output in Beijing Municipal from 2008–2022.

Year	Construction waste (million tons)	Demolition waste (million tons)	Total (million tons)
2008	7.95	23.39	31.34
2009	9.25	10.07	19.31
2010	11.98	15.14	27.13
2011	14.86	16.19	31.05
2012	16.96	16.24	33.20
2013	20.05	19.81	39.86
2014	22.99	19.74	42.73
2015	24.33	15.78	40.11
2016	24.87	14.39	39.26
2017	26.57	16.80	43.37
2018	29.29	19.69	48.98
2019	32.79	23.37	56.16
2020	36.06	21.10	57.16
2021	37.10	18.93	56.03
2022	36.58	15.02	51.61

Waste trend

Figure 1 shows the distribution of CDW generated in Beijing from 2008 to 2022. From the increase in C_W generation is likely due to the rapid urbanization and economic development of Beijing in recent years. On average, construction waste (C_W) is the largest component of CDW, accounting for about 57% of the total waste generated within the study period and it is closely followed by demolition waste (D_W) which accounts for 43% of the overall CDW generated.

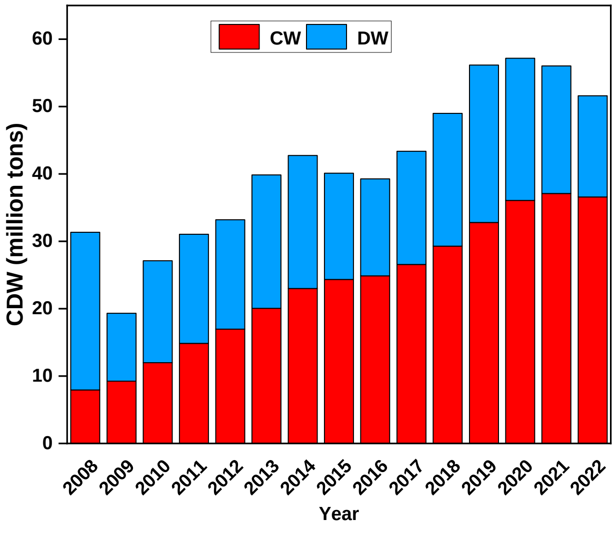

Figure 1 Beijing CDRW quantity due to construction activities.

From the analysis of the results in Table 3, the proportion of demolition waste to the total CDW production was always more than 50% between 2008-2011. This indicates that the quantity of demolition waste exceeded that of construction waste. Specifically, in 2008, 2009, 2010 and 2011, demolition waste accounted for 74%, 52%, 56% and 52% of total CDW respectively. Nevertheless, since 2012, this trend has reversed due to an increase in the proportion of construction. For example, the Daxing International Airport construction and the 2022 Winter Olympic infrastructural improvements in Beijing in recent years, also immensely contributed to the increase in construction and renovation/decoration waste [43].

Waste composition

The composition of waste materials for construction and demolition activities is presented in Table 4 below. The main components of CDW generated in Beijing are concrete, brick/block, mortar, metals, wood, brick and glass [43]. From the context of source, these wastes are generated by large-scale projects such as construction, demolition and renovation/decoration activities in Beijing. The dominant components of CDW generated in Beijing are concrete, brick/block, and mortar. Together, they constitute more than 85% of the total CDW. Waste concrete, bricks and mortar constitutes 54.3%, 17.4% and 14.4% of CDW, respectively. The percentage of waste concrete generated during construction and demolition activities is very high compare to other wastes because most structures that are built in Beijing these days use concrete. Due to the material's strength, durability, and fire resistance, concrete and reinforced concrete are utilized extensively. In addition to having a long history of use in Chinese architecture, brick and block continue to be the primary building materials.

As Beijing's urbanization and development accelerate, large volumes of concrete and masonry debris are produced as old structures are demolished and new ones are constructed. While the disposal of this construction and demolition waste poses environmental challenges, there are opportunities for recycling. Concrete and masonry demolition debris can be crushed and processed into recycled aggregate, which can partially replace virgin materials in new concrete. Promoting recycling will be essential for minimizing the environmental impacts associated with managing the predominant C&D waste types in Beijing.

Table 4 Compositions of CDW

Type	Mass percentage（%）
Steel	4.6
Wood	1.1
Plastic	2.3
Aluminium	0.7
Glass	0.2
Brick	17.4
Concrete	54.3
Mortar	14.4
Ceramic tile	3.7
Subtotal	89.7
Mixed fragments	1.4
Total	100.0

Prediction

The growth and progress of the construction sector are intricately linked to the investment requirements of one of the key components of national economic development, commonly referred to as the “troikas”. In 2003, the construction industry of China grew by more than 20%, and it has since kept up its rapid growth [44]. Within the framework of the Chinese declining GDP growth and the diminishing growth of fixed assets investment, the construction industry of China growth rate expansion is likewise exhibiting a downward trajectory. By observing the average annual growth rate of floorspace under construction (C_A) in Beijing in recent years, from 2015 to 2022, the annual growth rate of the area in Beijing is about 6%. According to historical data, the completion rate of building area in the construction industry has always remained above 40%. Therefore, it is possible to calculate the annual completed floorspace for the next few years based on this, and then calculate the new construction area. For 2022, the existing statistical data in Table 1 shows that the floorspace of buildings under construction in the construction industry of Beijing has a year-on-year growth ranging from -1.4% to 10% between 2020 to 2022. Therefore, it is assumed that from 2023 to 2033, the growth rate of construction activities will decrease. With the slowdown of fixed assets investment, the development rate of the construction industry is also slowing down accordingly. The relevant data on the operation of the national economy released by the National Bureau of Statistics shows that the year-on-year growth of the total output value of the national construction industry continued to slow down from 2015 to 2022 (between 2% and 11%). The floorspace completed in each year for the next few years can be calculated based on this same approach and a growth of -1%. Using this value, the demolition area (D_A) was obtained. Using 2022 as the baseline for analysis, projection of the future generation of CDW throughout the forthcoming years are made. The forecast results of the annual production of CDW from 2023 to 2033 are shown in Figure 2 below. Construction waste production in Beijing is expected to slightly rise over the years between 2023 and 2033, according to forecast data. The yearly output of waste from the construction industry is expected to reach 55 million tons by 2033 with an average growth rate of 0.68% annually.

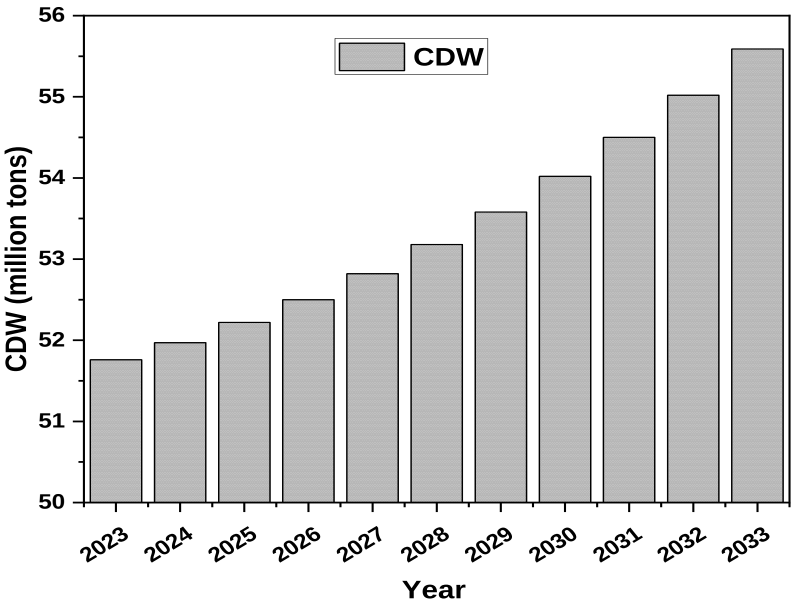

Figure 2 Forecasted values of CDRW generation in Beijing from 2023-2033

CONCLUSION

This study aimed to provide the first reliable estimates of construction and demolition waste trends in Beijing using empirical data and reasonable assumptions. The results indicate that between 2008 to 2022, Beijing's annual CDW increased over 4-fold from 31 million to 52 million tons due to massive new construction and demolition works. Concrete, bricks and other masonry materials accounted for over 80% total waste composition. Based on a -1% floorspace growth and 40% completion rate, CDW generation was projected to reach 55 million tons by 2033 if left unmitigated.

The exponential rise in waste generation significantly outpaces Beijing's utilization capacities, emphasizing the urgent need to advance waste sorting, recycling and sustainable management under circular economy principles. Although the slowed 0.68% projected growth rate may reflect wider construction industry changes rather than climate policies per se, the lack of linkage with economy-wide decarbonization warrants further research. Still, the scalable quantification methodology could help other developing cities plan appropriate waste facilities and policies.

While providing reasonable first CDW estimates for Beijing, certain limitations persist. Omission of excavation waste results in under counting, while estimated demolition rates and growth assumptions incorporate uncertainty without sensitivity analysis. Moving forward, integrating site-level waste audits with city-wide modeling and tracking construction's carbon footprint would strengthen evidentiary foundations for national policymaking. Exploring feasibility of ambitious reuse targets also remains vital.

In conclusion, this exploratory study generated new insights and an adaptable methodology to tackle the under-researched yet critically important issue of managing exponential construction waste increases in rapidly expanding cities like Beijing. Further research is warranted to enhance quantification, connect localized waste data to emissions reductions trajectories, and realize circular economy goals.

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