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Challenges and Opportunities of Aging Houses and Construction and Demolition Waste in Taiwan

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Abstract: Sustainable construction and demolition waste (CDW) management have been widely discussed. For a city seeking urban renewal or transformation, aging houses are remodeled, which creates a large amount of CDW. Taiwan is located in an earthquake-prone area with many aging houses. Sustainable CDW management is extremely urgent for such cities or countries. This study presented the current CDW state in Taiwan and suggested possible management strategies. Material flow analysis was conducted to understand the use and distribution of the construction materials. This shows that 100% of the raw material of concrete is imported, whereas 100% of the raw material of brick is domestic. Half of recycled steel is used as a raw material in steel products. The predicted CDW from aging houses was calculated and could be a sustainable source for these materials. However, waste concrete and brick are currently mostly used as subgrade filling materials but are not recycled to produce new construction materials. There are three obvious challenges in CDW management: the lack of cost-effective recycling technology, the increasing quantity of CDW, and the limits of refilled land and landfill volume. However, three opportunities have also emerged: the high potential for reducing carbon emissions from CDW, improved recycling technology, and increasing awareness of the circular economy. This study concludes that reducing the amount of CDW, increasing the lifespan of buildings, increasing the use of reuse or recycled CDW, and proper management of final waste disposal help reduce waste and build a nearly zero-carbon-emission construction industry.

Keywords: construction and demolition waste (CDW); aging houses; urban renewal; material flow analysis; sustainable management

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1. Introduction

Construction and demolition waste (CDW) includes waste materials generated from construction and demolition projects. These materials vary widely, and most are inorganic and not incinerated. If CDW is not recycled or reused, most of it ends up in landfills. Generally, CDW accounts for 25–30% of landfill space [1]. The successful recycling or reuse of CDW is complex and involves recycling technology, government policies, economic markets, and even waste treatment fees [2–5]. Luangcharoenrat et al. [6] compiled data from various countries and reported that CDW accounts for 19–60% of landfill space. According to the U.S. Environmental Protection Agency (EPA) [7], the U.S. has sharply increased waste since 1996. In the EU in 2018, over 800 million metric tons of waste were generated annually [8]. Mineral waste is the largest category of construction waste. The rapid growth in CDW has become an issue that cannot be ignored. As society progresses and infrastructure continuously updates and expands, the number of public and private buildings increases yearly. Without proper management, the resulting CDW will become a significant issue.

The quantity of CDW is highly related to urban development and is a direct consequence of urbanization and economic development [9,10]. Therefore, with increasing urbanization, the CDW increases as well. In developing countries or cities, CDW has undergone rapid development; for example, in China, annual CDW generation increased by 10% in 2019, and the recycling rate was less than 5% [11]. Effective CDW management is required more in developing countries or cities than in developed ones. There have been numerous studies on CDW management, mainly from an environmental management perspective, focusing on reducing the threat of CDW to the environment and landfill space. However, it rarely connects the link between aging houses and CDW. When a city has old buildings or outdated infrastructures, the city will seek urban renewal to improve its appearance and the quality of buildings to protect citizens' lives and property. This developing city is expected to generate massive amounts of CDW. The proportion of aging buildings is growing annually in Taiwan. According to the Ministry of the Interior's statistics platform (Real Estate Information Platform, https://pip.moi.gov.tw/V3/Default.aspx (accessed on 3 May 2024)), 34.0% of the buildings were over 40 years old, a 22.0% increase from 2011. Compared with other countries, Taiwan faces a surge in demolition projects, leading to a significant increase in CDW in the future. The demolition floor area was 2.5 million m^2 in 2023 but only 1.5 million m^2 in 2006. In recent years, the total CDW has exceeded 2 million tons every year. Therefore, the sustainable management of CDW in Taiwan and other urban renewal countries is very important.

Under the global goal of achieving net-zero carbon emissions by 2050, the construction industry accounts for more than one-third of the world's total carbon emissions. UNEP (2021) [12] reported that the global floor area increased by 21% from 2010 to 2019, CO_2 emissions increased by 8%, and energy use increased by 7%. The share of buildings in global energy is 36%, and the share of global carbon emissions is 37%. During social and economic development, the construction industry has faced a large challenge in terms of carbon reduction. Reducing carbon emissions throughout the entire life cycle of the construction industry, from construction materials to CDW management, has become a key issue for national net-zero emission targets. In Chau's review [13], energy use dominated the use phase, and the second important phase was the embodied phase. In Zhang and Wang's study [14], the building materials manufacturing stage contributed to 73% of carbon emissions, and the building operation stage contributed to 24%. The use and production stages in the construction life cycle generate the most carbon emissions [15,16]. Although the direct carbon emission of the end-of-life stage is small, recycled CDW materials can not only reduce waste generation but also reduce greenhouse gas emissions of embodied construction materials. For example, Peng et al. [17] quantified the carbon emission reduction potential from recycled CDW. Oh et al. [18] used demolished building materials and waste concrete powder as cement substitute materials and presented carbon reduction effects. Recycling can decrease carbon emissions for both the raw material production and waste stages, helping to reduce overall carbon emissions in the construction industry.

There are many challenges in managing CDW, but there are also some opportunities to improve it. Taking Taiwan as an example, this study has three objectives. The first is to address the CDW status in Taiwan, including the distribution of construction materials. The second is to show the aging houses and the projection of possible CDW. The third is the discussion of effective CDW management for developing cities, including discussions on their challenges and opportunities.

2. Materials and Methods

2.1. CDW in Taiwan: Definition, Quantity, and Waste Types and Disposals

In Taiwan, construction waste is categorized into two types, with different authority agencies. The first type is the general waste from construction, building demolition, renovation projects, and ground clearing. The construction waste materials, including concrete, metal scraps, glass fragments, plastic, wood shavings, bamboo pieces, paper scraps, and asphalt, are considered general industrial waste and fall under the jurisdiction of the Ministry of Environment (MoE), according to the Waste Disposal Act. The second type consists of leftover soil, rocks, bricks, and concrete blocks produced during building construction and public work. The second type is considered a useful resource and is not classified as waste, but it sometimes mixes with some waste from the construction site. It is called construction soil and rock debris. When these materials are temporarily stored, stockpiled for recovery, sorted, processed, transferred, or reused, they are considered useful soil and gravel resources. The responsible authority is the Construction and Planning Agency of the Ministry of the Interior. Thus, the management of leftover soil and rock debris from construction is overseen by the Construction and Planning Agency, while construction waste is the responsibility of the MoE. Figure 1 shows the CDW definition in Taiwan.

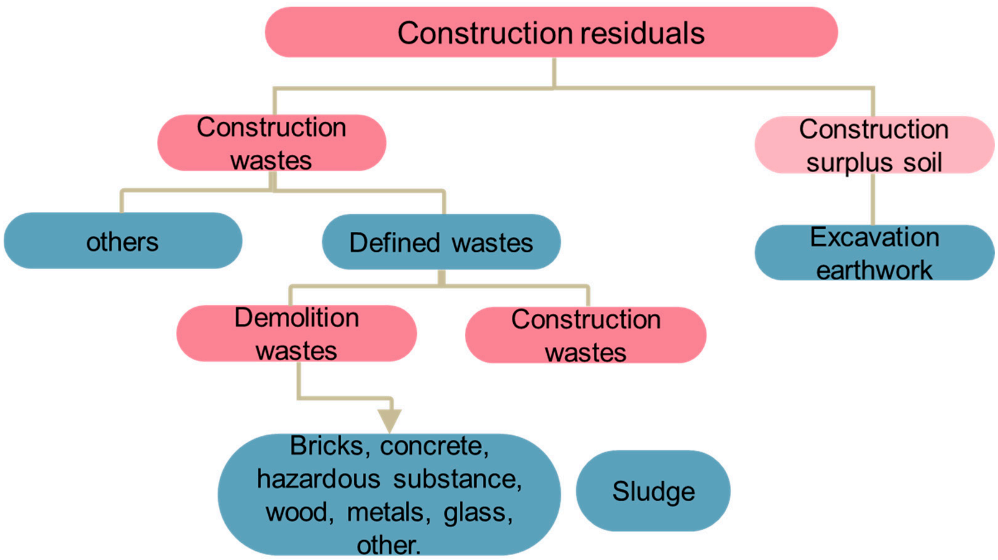


Figure 1. Definition and process flow of CDW in Taiwan (the figure was created by the authors).

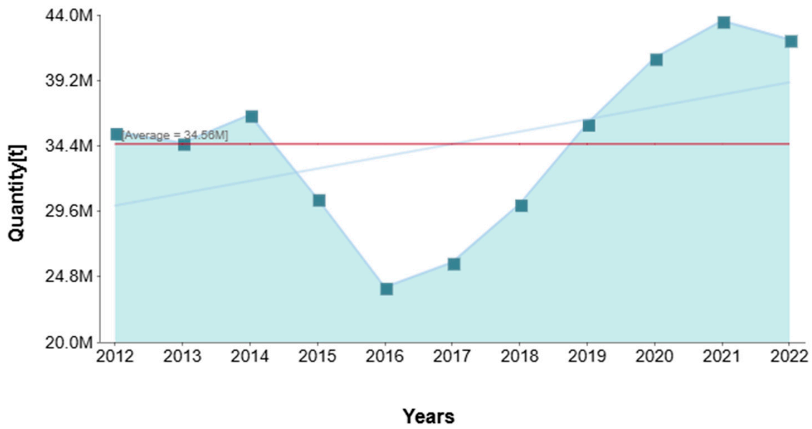
In addition to these two types, there is also waste from renovation and repair projects, which is also classified as construction waste. If a business generates this waste, it is classified as industrial waste and must be legally disposed of or recycled. If a household or nonbusiness entity contracts a construction company for renovation or repair work, it is also considered industrial waste. However, if the household or nonbusiness entity performs the renovation themselves, the waste is classified as general waste. The data survey from renovation and repair waste is difficult because it is not well divided and recorded and is not discussed in this study.

With respect to both domestic and international definitions of construction waste, this study has summarized the types of construction waste as follows:

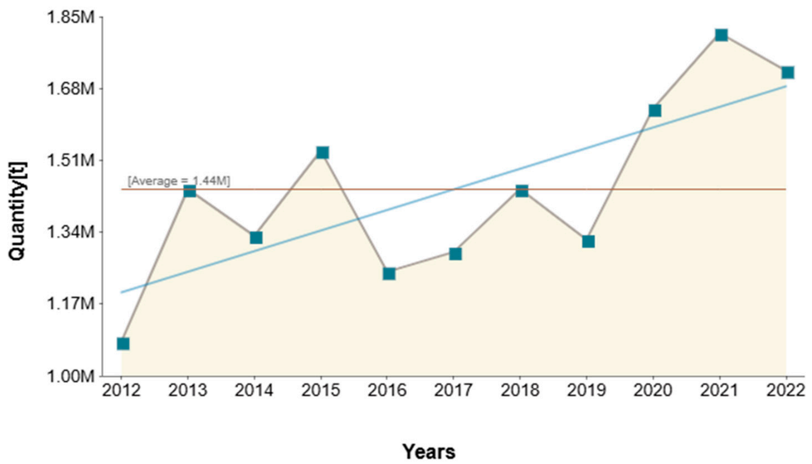
- Leftover soil and rock debris refer to sand, stones, and soil generated from excavation during construction projects, which are resources that can be directly reused;
- Building construction waste can be further divided into construction-phase waste and demolition-phase waste, depending on the stage of the building lifecycle;

- Demolition waste refers to waste produced after the demolition of a building. It includes various types of waste materials from the building's main structure, such as concrete blocks and scrap steel, as well as waste from renovation materials, such as bricks, waste wood, metals, and glass. Additionally, it includes hazardous materials such as asbestos and other materials such as plastic and paper.

For construction, soil and rock debris in 2012–2022 in Taiwan averaged 34,561,287 m^3 (Figure 2A). The quantity is highly related to public construction projects and the housing market that year. The quantity in the past 10 years varied between 25 million m^3 and 40 million m^3. The classification of leftover soil and rock debris by soil condition is categorized using soil codes ranging from B1B7 and reused for different construction materials. The leftover soil and rock debris produced at construction sites can be considered to be directly reused if they are reused at the same site. It is considered an indirect reuse if it is transported to treatment facilities and then used through transfer or processing. The direct reuse rate was approximately 23%, and 77% was indirect reuse. Although 100% can be reused, 16% of indirect reuse is stored and has not yet been reused. Therefore, the reuse conditions of construction soil and rock debris should include 23% direct reuse, 16% storage, and 61% indirect reuse.



(**A**)



(**B**)

Figure 2. Production of construction soil and rock debris and construction waste in Taiwan. (**A**) Construction soil and rock debris (m^3) and (**B**) construction waste (tons). (Data sources: (**A**) is from the Construction of the Surplus Earthwork Information Service Center, https://www.soilmove.tw/ (accessed on 20 May 2024), (**B**) the Resource Circulation Administration, Ministry of Environment, Industrial Waste Declaration volume statistical report. https://waste.moenv.gov.tw/RWD/Statistics/?page=Year1 (accessed on 20 May 2024)).

Construction waste, including construction mixtures (classified as R-0503) and civil or construction waste mixtures (classified as D-0599), is reported by construction companies, recycling operators, and waste treatment operators. The classification R-0503 accounts for most of the construction waste, and the average annual construction waste (R-0503) in Taiwan is 1,442,077 tons (2012–2022) (Figure 2B). With the increasing pace of urbanization and the promotion of urban renewal projects, the production of construction waste began to rise annually from 2016 to 2021, reaching a peak output of approximately 18.11 million tons, the highest in nearly a decade.

Figure 3 shows photographs of the construction soil and rock debris, and construction waste. The difference between the waste components can be clearly observed.

(**A**) Construction soil and rock debris

(**B**) Construction waste

Figure 3. Photograph of construction soil and rock debris, and construction waste (photos were shot by the authors).

Unlike construction soil and rock debris, which can be directly reused as resources, construction waste includes different compounds and should be sorted for different reuse or recycling purposes. Table 1 shows the general reuse and recycling of construction waste materials in Taiwan. Generally, inorganic concrete and brick materials are reused as secondary filling materials, and their final disposal is landfill. Glass and steel are recycled as new materials. Organic materials, such as wood, paper, and plastic, can be recycled as materials or as fuel for incineration. They have no landfill demand. This table shows the general status of CDW waste materials, and it also implies that there is an urgent need for improved concrete or brick recycling.

Table 1. Reuse, recycling, and final disposal of construction waste in Taiwan.

Types of Waste	Reuse or Recycle	Final Disposal
Concrete	Direct reuse: filling material for landfills or roads. Recycle: recycled aggregate	Landfill
Brick/tiles	Direct reuse: filling material for landfills or roads.	Landfill
Glass	Recycle: recycled glass	Landfill (few)
Steel	Recycle: recycled steel	Recycle
Other metals, such as copper and aluminum	Recycle: recycled metals	Recycle
Paper	Recycle: recycled paper	Incineration
Wood	Direct reuse: fuel, compost, reused wood.	Incineration/Landfill
Plastic	Recycle: recycled plastic	Recycle

Data sources: The authors created the table.

The official data provide the total construction waste quantity but no details of the waste. Therefore, we surveyed 3 construction waste treatment plants and summarized the compound distribution of construction waste in Taiwan. Figure 4 shows the results. Among the construction waste, rock, gravel, and sand account for 52%, and concrete and brick accounts for 32%. The mixed soil content was 9%. They constitute the majority of the construction waste, accounting for 93% of the total waste. The others are waste plastic (4%) and waste wood and paper (3%). There are no steel or other metal data because the metal is collected and transported to metal plants, not construction waste treatment plants. The compositions and proportions of CDW differ among countries; for other countries, concrete, brick, and mortar accounted for more than half. For example, in China, more than 60% of wood waste is produced, and the amount of wood waste in CDW is greater than that in other countries [19].

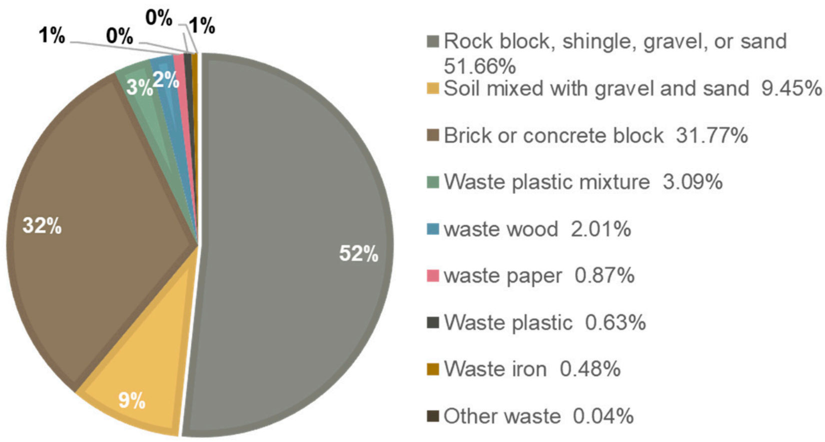


Figure 4. Compound distribution of construction waste (R-0503). The data were obtained from 3 local CDW treatment plants: Sunshine City Development Co., Ltd., New Taipei City, Taiwan, Dezhan Sand and Gravel Co., Ltd., Taipei City, Taiwan, and Yisheng Recycling Co., Ltd., New Taipei City, Taiwan.

2.2. Calculation of the Possible CDW Amount from Aging Houses

In Taiwan, before a construction site is demolished, the construction company needs to apply for permission for construction demolition and submit a waste cleanup plan. In the waste cleanup plan, a predicted CDW quantity needs to be given. This projected CDW is calculated using the official coefficients provided by the MoE, such as those in Table 2. This table shows the construction waste prediction coefficients. Because demolition waste is regarded as industrial waste and is under supervision, the demolition site is the source of waste, and the demolition plan and the predicted waste quantity must be submitted. The projected waste is obtained from the floor area (m^2) × waste generation coefficient

(m^3/m^2) × waste density ($tons/m^3$). According to the regulation, the default density of waste is 0.6 $tons/m^3$. Therefore, when the floor area of aging houses is obtained, the waste generation coefficient and the default density are then used to calculate the projected CDW from aging houses.

Table 2. Waste generation coefficients of demolition and construction. (unit: m^3/m^2).

Type	Structure	Buildings				
		House	Factory	Classroom	Office	Others
Demolition	Reinforced brick	0.852	0.741	0.79	0.79	0.79
	Brick	0.74	0.79	0.79	0.79	0.79
	Reinforced Concrete (RC)	0.822	0.67	0.704	0.79	0.79
	Steel	0.649	0.61	0.79	0.79	0.79
Construction	Reinforced Concrete (RC)	0.124	0.081	0.098	0.098	0.134
	Steel Reinforced Concrete (SRC)	0.135	0.105	0.08	0.107	0.134
	Steel Structure (SS)	0.103	0.106	0.08	0.09	0.134
	Steel	0.09	0.102	0.08	0.08	0.134

Data source: Construction waste clean plan, Ministry of Environment (Data can be accessed at https://waste3.moenv.gov.tw/download/waste_web/cleanprog/20131212/(%E4%BA%8C%E5%8D%81%E5%9B%9B%E3, accessed on 11 March 2024).

2.3. Data Used for Material Flow Analysis

Material flow analysis helps to demonstrate the flow of materials from raw sources to disposal. There are many types of CDW, and three major construction materials are discussed in this study. They are concrete, steel, and bricks/tiles. To understand their flow, the raw materials, products, and disposal or reuse/recycling processes were investigated. The data shown in this study are based on 2022 data.

The raw materials used to produce concrete, steel, and brick/tiles are collected from official data, including statistical data from the Ministry of Finance, the Ministry of Economic Affairs, and annual reports from industry associations. The raw materials are obtained from imports or domestic yields. According to the import and domestic production data from 2022, the import and domestic production volumes of raw materials, finished products, and remaining soil and stone are shown in Tables 3 and 4. The primary types of raw materials imported by Taiwan's construction industry include steel, metal ores, stones, and clay. As shown in Table 3, the largest imported raw material is sand, at approximately 74 million tons, followed by metal ores at approximately 22 million tons, and crushed stone at approximately 18 million tons. The primary types of domestically produced raw materials in Taiwan's construction industry include sand, stone, and cement (Table 4). The largest domestically produced raw material is sand, at approximately 66 million tons, followed by stone, at approximately 16 million tons, and cement, at approximately 11 million tons.

The quantity of construction-related products in 2022 is summarized in Table 5. This will facilitate subsequent research activities focused on these products. Currently, the types of products discussed in this study include concrete, bricks, and steel, with concrete being the most widely used, and the quantity is 72 million tons. The products are linked to raw materials and then are in a use state or waste. The waste data used the CDW quantity and the component percentage in Section 2.1. The composition ratio of the products and the recycling and reuse rates are also important indicators of waste recycling. The reuse rates of the products are shown in Table 6. The waste concrete, tiles, or bricks are reused as filling materials, not recycled, and the reuse rate is less than 40%. However, steel has a high recycling rate of up to 95%.

Table 3. Imported raw materials of concrete, steel, and brick/tiles in 2022.

Raw Materials		Imported Quantity (ton)	Total (ton)
	Waste steel	2,927,734	2,927,734
	Metal ores	22,551,302	22,551,302
Stone/ gravel	Marble and limestone	82,544	7,628,087
	Granite, basalt, sandstone	350,759	
	Gravel	4,810,909	
	Natural sand	1,836,888	
	Kaolin	546,987	
Cement	Limestone	3,230,961	7,111,199
	Quicklime, slake lime, hydraulic lime	455,343	
	Portland cement	3,424,895	
	Clay	449,908	449,908
	Silica sand	1,491,369	1,491,369
	Cement	3,993,351	3,993,351
	Sand	74,190,000	74,190,000
	Crushed stone	17,840,000	17,840,000

Data sources: The steel data were obtained from the Steel Information Annual Report released by the Taiwan Iron and Steel Industry Association. The other imported data were accessed by the Ministry of Finance, Customs Department import and export inquiries. Available online: https://portal.sw.nat.gov.tw/APGA/GA30, accessed on 23 April 2024.

Table 4. The raw concrete, steel, and brick/tiles materials domestically produced in 2022.

Raw Materials		Domestic Quantity (ton)	Total (ton)
Sand	Sand	31,290,000	66,234,000
	Crushed stone	29,983,500	
	Graded material	2,263,500	
	Other	2,697,000	
Stone	Marble	16,421,693	16,538,840
	Limestone	92	
	Serpentine	51,299	
	Dolomite	13,746	
	Others	52,010	
Cement		11,223,473	11,223,473

Data sources: Ministry of Economic Affairs. Industrial Production, Shipment & Inventory Statistics Survey. Available online: https://dmz26.moea.gov.tw/GMWeb/investigate/InvestigateDA.aspx, accessed on 19 April 2024.

Table 5. Quantity of construction-related products in 2022.

Products	Quantity (ton)
Ready-mixed concrete	72,870,000
Aluminum doors and windows	47,284
Ceramic tiles	1,149,667
Red brick	1,709,023
Steel	6,809,333
Wire rod	1,714,211
Section steel	1,417,448
Hot-rolled band	15,767,642

Data sources: Ministry of Economic Affairs. Industrial Production, Shipment & Inventory Statistics Survey. Available online: https://dmz26.moea.gov.tw/GMWeb/investigate/InvestigateDA.aspx, accessed on 19 April 2024.

Table 6. Reuse and recycling rates of major construction products.

Products	Reuse or Recycling Rate	Data Sources
Ready-mixed concretes	35%	Taiwan Professional Civil Engineers Association
Ceramic tiles	20%	Taiwan Building Center
Red bricks	40%	Taiwan Building Center
Steels	95%	Steel Information Annual Report

2.4. Status of Aging Houses in Taiwan

Taiwan is located in an earthquake-prone area, and the building codes were upgraded after a large earthquake in 1999 to ensure the safety of buildings as well as public constructions. Therefore, old buildings that were not built with upgraded regulations would have safety concerns. In addition, aging houses are facing urban renewal to improve land utility. It tends to rebuild old buildings into new and higher buildings to increase the floor area. Aging houses will generate considerable CDW in the near future.

The house data are accessed from the Ministry of the Interior's statistics. They release the house information every quarter and have a real estate information platform, https://pip.moi.gov.tw/V3/Default.aspx (accessed on 22 December 2024). According to the house statistics from the 2022 report. In the past 10 years (2011–2022) in Taiwan, the number of houses has increased by 1 million, and the median house age has increased from 2430 years. In 2011, 12% of the houses were older than 40 years of age, but in 2022, 34% were older than 40 years. Figure 5 shows the percentage of the ages of the houses in Taiwan in recent years. After 2019, the number of old houses (>40) was greater than that of young houses (<20). Compared with other cities, the two early developed cities, Taipei and Kaohsiung City, have more aging houses, especially the capital city, Taipei City, where the number of houses over 40 years is nearly 430,000, accounting for 45.51%. The number of houses over 30 years of age reached 71.98%, meaning that 10 years later, more than 70% of the houses were older than 40 years. Figure 6 shows the ages of the houses in the 6 urban cities in Taiwan.

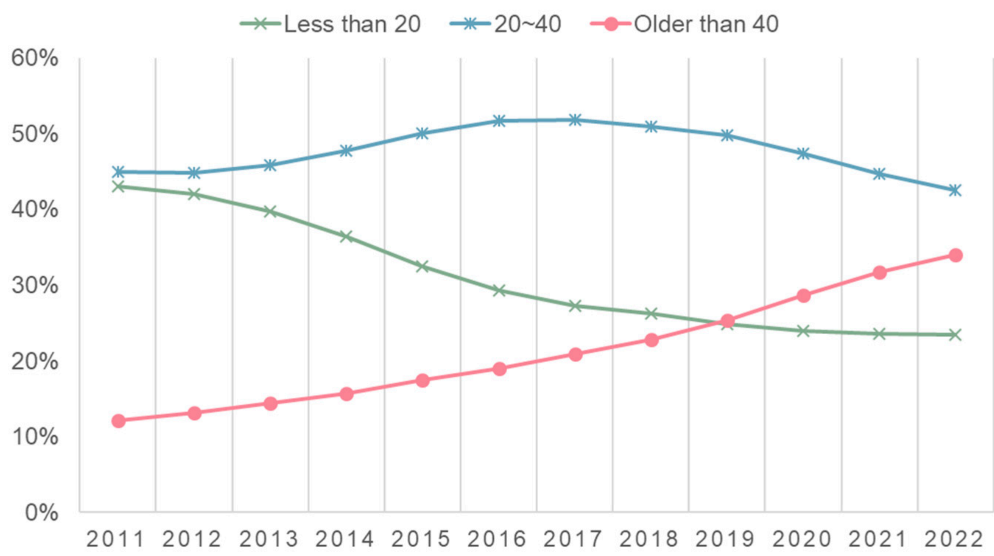


Figure 5. Percentage of house ages in Taiwan from 2011 to 2022. (Data source: Real Estate Information Platform, Ministry of the Interior https://pip.moi.gov.tw/V3/Default.aspx (accessed on 22 December 2024). The quarter report, Housing Statistics, 2nd Quarter, 2022, (10/2022), Table 2-3-2 (pp. 138–139)).

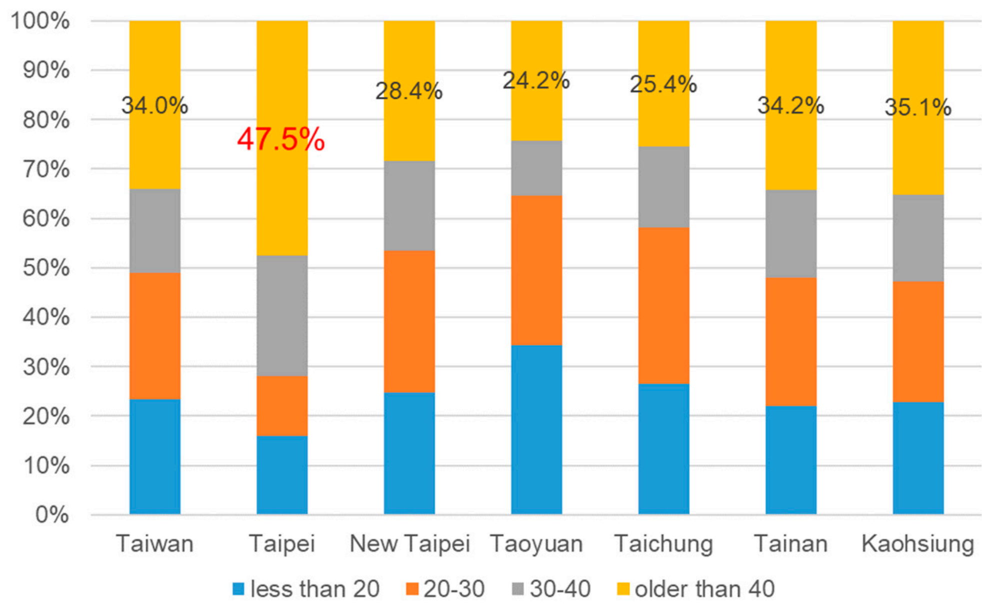


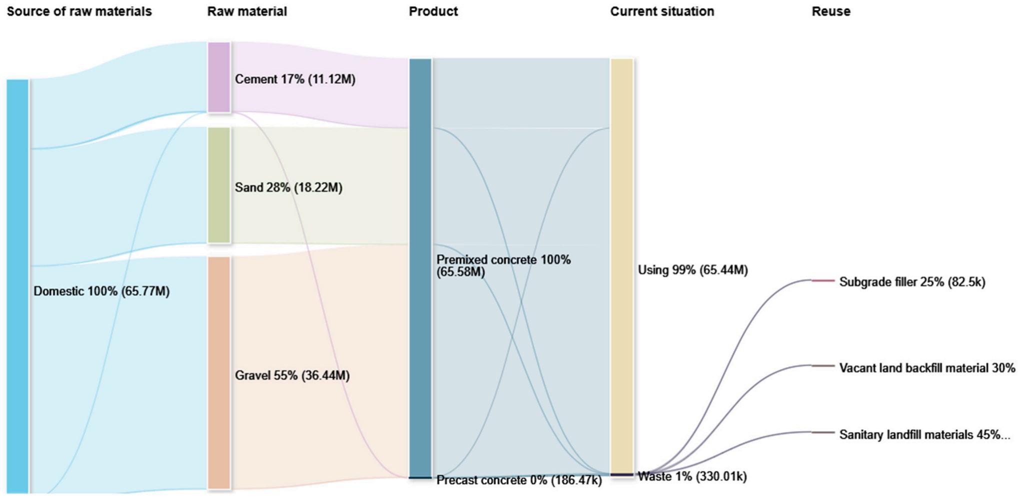
Figure 6. House age in different cities in Taiwan (2022). (Data source: Real Estate Information Platform, Ministry of the Interior https://pip.moi.gov.tw/V3/Default.aspx (accessed on 22 December 2024). The quarter report, Housing Statistics, 2nd Quarter, 2022, (10/2022), Table 2-3-2 (p. 138–139)).

3. Results and Discussion

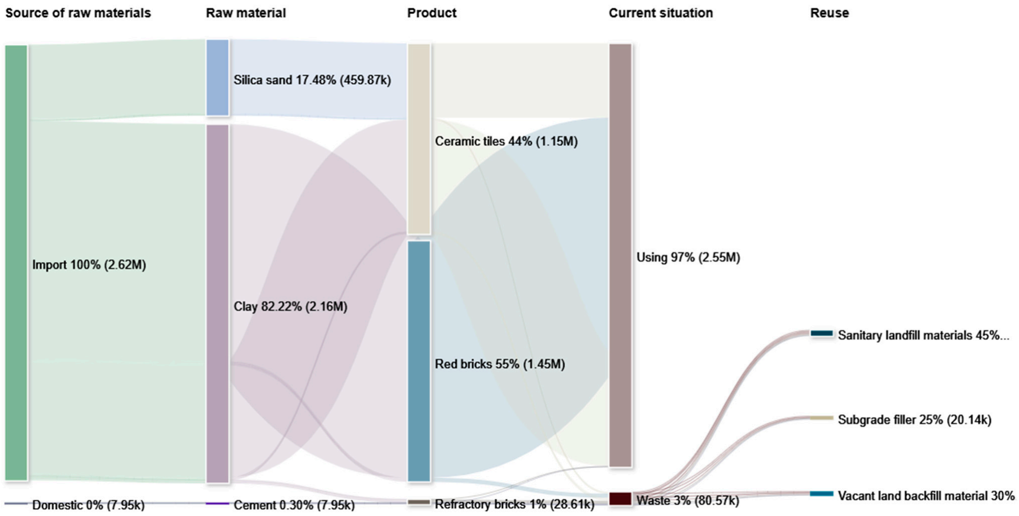
3.1. Results of Material Flow: Concrete, Steel, and Brick

Understanding the flow of construction materials helps clarify the benefits of the reuse or recycling of CDW. If the CDW turns into material resources, it helps reduce the need for raw construction materials. The material flow is divided into four main categories: sources, raw materials, finished products, and the current situation. Because the materials are used for construction, most of them are in use. Waste might be generated from old materials, not the new materials of that year. However, waste can potentially reduce the amount of raw material in that year, which is considered in the flow analysis. The proportions of raw materials, finished products, and waste were calculated using the ratios for finished products and recyclable reuse rates. The Sankey diagram was created using ChartExpo and categorized into three major types: steel, brick, and concrete, as shown in Figure 6. Ten years of data were collected, and the data show the results of 2022.

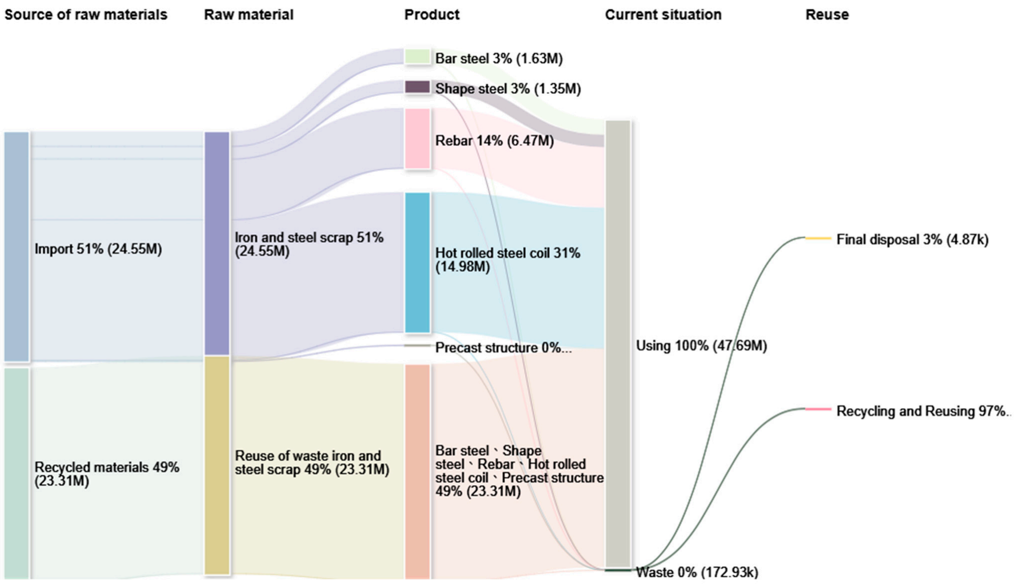
Figure 7A shows the flow of the concrete material. The source of raw materials is 100% domestic, consisting of cement (11.12 M), sand and gravel (18.22 M), and aggregates (36.44 M). The finished product is predominantly ready-mixed concrete (88.54 M), followed by precast products. The concrete waste is 100% reused, but all of the waste is subgrade filling materials, including sanitary landfill materials (45%), subgrade fill materials (25%), and backfill materials for vacant land (30%). This results in a reuse rate close to 100%. Many demolition construction projects involve removing concrete foundations, roads, sidewalks, walls, and other structures, generating a significant amount of concrete waste, which is typically discarded. Currently, most waste concrete is reused as a filling material and rarely returns to raw materials or concrete products. A deeper exploration of the final impacts is crucial in considering sustainable development.



(**A**) concrete



(**B**) brick



(**C**) steel

Figure 7. Material flow results of major construction materials in Taiwan. (**A**) Concrete, (**B**) brick, and (**C**) steel.

Figure 7B presents the flow of brick materials. The source of raw material is almost completely imported, with the exception of cement. The primary raw materials include cement (7.95 K), silica sand (459.87 K), and clay (2.16 M). The finished products, which are commonly used in industry, consist of ceramic tiles (1.15 M), red bricks (1.45 M), and refractory bricks (28.61 K). Based on practical recyclable ratios, the recyclable proportion of bricks is approximately 26% (1.09 M) of the total, whereas the remaining 74% (3.03 M) enters the final disposal stage. The construction waste treatment methods for bricks are typically processed together with concrete, which is also used as landfill materials, backfill, or subgrade fill; the final disposal method involves a secure landfill. Considering the cost, the industry does not want to use waste bricks as raw materials. However, the production of new bricks requires a significant amount of energy, particularly in the high-temperature firing process in kilns. If recycled bricks can be used, energy can be saved, and the associated carbon emissions can be reduced. Therefore, recycling bricks could significantly reduce the overall greenhouse gas emissions associated with brick production.

Figure 7C presents the Sankey diagram for the steel materials. The sources of raw materials are divided into 51% imported steel and 49% recycled steel. The primary raw material is scrap steel (24.55 M), with an additional category for recycled scrap steel amounting to 23.32 M. The finished products are generally categorized as rebar (1.63 M), shaped steel (1.35 M), reinforcing steel (6.47 M), and hot-rolled steel coils (14.98 M). On the basis of commonly used practical recyclable ratios, the recycling rate for waste steel is approximately 97%, whereas the remaining 3% enters the final disposal stage. The recycled materials are typically reused to produce recycled steel for continued use, which differs from concrete and brick, in which the recycling rates are very low. The nonrecyclable portion is usually treated together with waste concrete. Recycling steel saves valuable resources and significantly reduces the need to re-extract and process raw materials by reusing scrap steel. Compared with the extraction of raw materials, this process can decrease coal and water consumption by approximately 40%. In practice, metal recycling plays a vital and critical role, and steel recycling manufacturing is very established. It is worth determining the carbon reduction potential of recycled steel further.

The material analysis of the three main construction materials revealed that there are some inconsistencies in the management of construction materials and waste. Notably, discrepancies exist between the quantities of raw materials and the amounts of recycled waste. An investigation revealed that some operators recycle substandard raw materials, leading to inconsistencies in material quantities and significantly affecting the accuracy of the data. To address this issue, future construction resource databases should consider operators' recycling practices to ensure the reliability of the data. Further research into waste recycling practices will also be undertaken to develop more efficient waste management solutions.

3.2. Results of the Potential CDW Generated from Aging Houses

Assuming that a house aged over 40 years would become CDW in the future, the potential CDW in the next 10 years can be projected by the floor area (m^2) and the waste generation coefficient (m^3/m^2) provided by official suggestions. Taking Taipei City as an example, the average residential area is 98.91 m^2, and the number of tax-registered houses aged over 40 years is 428,760. Therefore, the total area of buildings over 40 years old is 42,408,261.82 m^2. Applying the construction demolition generation waste coefficient, Taipei City is expected to generate approximately 34,867.7 million cubic meters of construction waste from buildings over 40 years of age. Calculating the weight at 0.6 tons per cubic meter results in 20,920.6 million tons of construction waste.

Table 7 summarizes the potential CDW in six urban cities in Taiwan. The average house area is 131.77 m^2. Because house prices are high in Taipei and New Taipei City, the average house area is smaller at less than 100 m^2. The total CDW is approximately 200 million tons in Taiwan, and Kaohsiung City would generate the highest quantity of CDW compared with other cities.

Table 7. Potential CDW generation from 40-year-old houses in different cities in Taiwan.

Cities	Average Floor Area per House (m^2)	Number of Buildings over 40 Years	The Potential Floor Area over 40 Years (m^2)	Projected CDW	
				m^3	ton
Taipei	98.91	428,760	42,408,651	34,859,911	20,915,947
New Taipei	97.12	475,560	46,186,387	37,965,210	22,779,126
Taoyun	135.34	214,040	28,968,173	23,811,838	14,287,103
Taichung	145.49	274,730	39,970,467	32,855,724	19,713,435
Tainan	157.26	246,269	38,728,262	31,834,632	19,100,779
Kaohsiung	129.22	386,664	49,964,722	41,071,001	24,642,601
Taiwan (National)	131.77	3,069,245	404,434,413	332,445,088	199,467,052

The major CDW materials are concrete and brick; waste is mostly used for filling materials. The demand for landfilling decreases with time, but the quantity of CDW increases. This will result in the demand being less than the supply, and the nonuse of storage or even illegal dumping might occur. Therefore, the effective management of CDW is important not only for the construction industry but also for the entire environment. Turning waste into material requires cost-effective technology; other management strategies are needed before acquiring technology.

3.3. Challenges and Opportunities in CDW Management in Taiwan

There are three obvious challenges to CDW management in Taiwan. The first is the lack of cost-effective recycling technology. Steel recycling technology is very well implemented, but it is not suitable for waste concrete and brick. The concrete and brick waste are usually crushed to a small size and become subgrade filling materials. This mixture was not turned back into recycled materials. The second is the increasing quantity of CDW. In Taiwan or other Asian countries, the required urban renewal would accelerate the quantity of CDW, and the current treatment plants or the filling needs might not be enough to handle the increasing CDW. The third is the limits of land space and landfill volume. The incinerable CDW, such as plastics or wood, can travel to incineration plants, but most CDW are inorganic compounds and can travel to landfills or landfilling materials. However, the available volume of land space and landfills is limited and cannot be expanded in the future. It cannot receive the projected increasing CDW. The worst case is that there is no adequate space for the CDW, and dumping waste may become illegal.

Although there are some challenges in CDW management, opportunities have also emerged. At least three opportunities can be found. The first is the high potential for carbon emission reduction in CDW. The treatment of CDW as a recycled product has a low manufacturing need, and the carbon emissions are expected to be lower than those of the raw material and its manufacture. Using recycled CDW can help reduce the amount of embodied carbon in the construction industry and reduce total carbon emissions in the life cycle of the entire industry, as shown in Figure 8. For example, Wang et al. [20] calculated the carbon reduction potential for CDW recycling in China and reported positive average growth rates in most areas. Zhao et al. [21] used a Japanese city as an example, Kitakyushu, where rapid growth in CDW and CDW recycling will soon contribute to a 1.9–6.8% carbon reduction in the construction industry because of the reduction in carbon emissions from the use of new materials. In addition, good sorting of CDW and subsidy fees can reduce carbon emissions [22]. The second opportunity is improved recycling technology. Conventionally, CDW is reused as a subgrade filling material. However, with the progress in recycling technology, CDW can be expected to be used as a new material, and its usage will be broader than before. The third opportunity is the increasing awareness of the circular economy. Given the circular economy, massive CDW is a large urban construction resource. Old buildings and constructions are the sources of construction materials. It can serve as an abundant supply of construction development, making cities more sustainable and enhancing urban renewal.

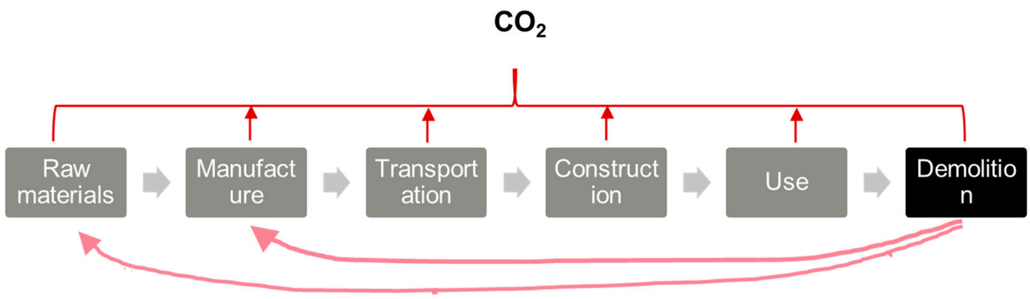


Figure 8. Carbon emissions in the construction industry and the potential reduction from recycled CDW.

The sustainable use of CDW materials is important but has not received much attention. The sustainable use of CDW not only fulfills the circular economy in the construction industry but also avoids illegal dumping and damage to the environment. If the demand for filling and supply of waste is not balanced in the future, illegal dumping may occur. The Waste Framework Directive (WFD), established by the European Union in 2008, serves as a blueprint for overall development, introducing a hierarchy of waste classification. This hierarchy includes five levels: prevention, preparing for reuse, recycling, recovery, and disposal. The directive was amended in 2018, with adjustments specifically targeting waste prevention. The primary objective of waste management policies is to reduce resource usage and protect natural resources by recycling waste and making good use of recycled materials, including energy recovery. In the entire waste management system, the highest priority is to take measures to prevent recycled materials from becoming waste. Following prevention, recycling is carried out, with disposal being the last resort for waste that cannot be recycled. The goals of waste management are to reduce the amount of waste and to reduce the potential adverse impacts of waste on the environment and human health. The rules of the WFD are perfectly used in CDW management.

The good management of CDW helps reduce waste, avoid illegal dumping, and help build a nearly zero-carbon-emission construction industry. The final recommendations are shown below (Figure 9).

1. Reducing the amount of construction and demolition waste

Minimizing the generation of construction waste relies on the initial design, construction, and demolition phases. To make an effective design, building information modeling is a tool to demonstrate buildings with effective usage of building materials and reduce the amount of waste materials [23–27]. Increasing the effective use of building materials avoids excessive material usage and associated carbon emissions. In particular, Wang et al. [24] developed a conceptual framework to assess carbon emissions over the life cycle of building demolition waste. These authors reported that recycling metal waste has far greater environmental benefits than recycling masonry waste. Xu et al. [28] proposed a BIM-based CDW management system to quantify CDW GHG emissions accurately. In addition, adopting different construction methods can help achieve this goal. For example, precast construction has been proven to reduce materials and carbon emissions more than cast-in-situ construction has [29–32].

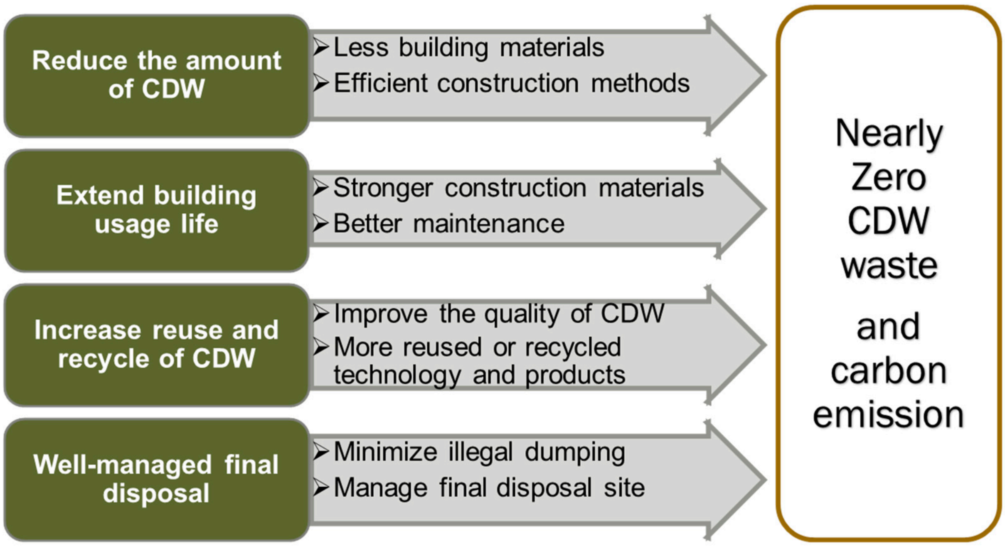


Figure 9. The suggestion of CDW management to achieve nearly zero carbon emissions.

2. Extending the lifespan of buildings

The average lifespan of a house is approximately 50 years, but with advancing technology, modern houses can last more than 100 years. The design and material choices of a building directly impact its lifespan. In the life cycle of buildings' carbon emissions, the usage/operation stage contributes the largest percentage of carbon emissions [33]. The choice of materials and the lifespan of technical solutions is as important as the choice of material [34,35]. However, considering the demolition waste, the longer the building operation is, the less CDW is generated, and the carbon emissions in the CDW stage can be reduced. This can be achieved through high-performance concrete, enhanced protection of rebar, or improved corrosion resistance in steel structures.

3. Increasing the use of reused or recycled construction and demolition waste

The construction industry has significant room for improvement in recycling practices. Overall, in 2020, the average recovery rate for construction waste in EU member states was 90% [36]. Since 2010, highly developed countries such as the Netherlands, Luxembourg, Ireland, Italy, and the UK have had recovery rates exceeding 90%. Slovakia and Cyprus, categorized as slowly developing countries, had recovery rates of approximately 60% before 2018, reaching the target only in 2020. Ref. [8] reported that the Netherlands, Denmark, and Luxembourg performed effective CDW management because of their most effective performance in source reduction, recycling, and landfilling. End-of-life concrete is considered a priority for CDW recycling in most EU countries. However, much of it is downgraded for reuse or even landfilled. According to data compiled by Zhang et al. [37], 96% of metal CDW was reused and recycled. Approximately 78% of the concrete and brick materials were downcycled for use as road base materials, whereas only 3% were used for concrete production. Therefore, increasing the return of recycled CDW to the construction industry is urgent. This can be achieved through public awareness campaigns, government regulations, and mandatory enforcement to encourage the reuse of recycled products. Such measures can effectively promote the recycling and proper disposal of demolition waste. There is a high carbon reduction potential for recycling construction waste [38]. Compared with ordinary concrete, recycled cement concrete results in an 85% reduction in carbon emissions [39]. The incorporation of CDW aggregates up to 20% in asphalt concrete for urban road pavement is a sustainable and feasible option [40].

4. Proper management of final waste disposal

Recycling CDW is clearly better than disposing of CDW. Marzouk and Azob [41] reported that recycling CDW leads to significant reductions in emissions and energy use and conserves landfill space compared with the disposal of wastes in landfills. However, partial CDW remains for final disposal. Construction waste often contains small amounts of hazardous substances, including heavy metals, asbestos, and fluorescent lights. Proper final disposal must be ensured when such waste cannot be recycled. Legislation can be enacted to regulate the transportation of construction waste to avoid illegal dumping. In addition, facilities or disposal sites should be supervised to maintain a safe site environment.

4. Conclusions

CDW management alleviates the demand for landfills and mitigates environmental pollution issues. Moreover, reducing waste materials leads to more efficient resource utilization, lowering the demand for raw materials and reducing the environmental impact of resource extraction. Sustainable management of CDW is a crucial step in helping the construction industry achieve net-zero emissions. This is related to incorporating recycled CDW materials into new construction, reducing the demand for mining and raw materials, and minimizing the final landfill volume. Without sustainable management of CDW, the increasing quantity of CDW generated from aging houses in the future could result in illegal dumping and environmental damage. This study presents the CDW status in Taiwan and provides several suggestions for similar cities in managing CDW. Some conclusions are summarized as follows:

1. In Taiwan, construction residuals are separated into waste and soil and rock debris. The waste is managed by the Ministry of Environment, and the soil and rock debris are under the regulations of the Ministry of the Interior. The annual CDW is approximately 2 million tons, and the annual amount of construction soil and rock debris is 40 million tons;
2. In Taiwan, the raw materials of concrete are 100% domestic, and those of brick are 100% imported. The CDW is now reused as a subgrade filling material, but the filling demand is ultimately limited;
3. More than one-third of buildings in urban cities in Taiwan are older than 40 years. With the development of urban renewal, potential CDW is expected;
4. Recycling CDW and returning to the construction industry are urgent issues, and they can directly reduce disposal amounts, prevent illegal dumping, and contribute to reducing carbon emissions in this industry's life cycle;
5. The challenges of large CDW are expected in developing cities, but there are opportunities. With the high potential for carbon emission reduction and the increasing circular economy, the CDW generated from aging houses could serve as a large urban construction resource;
6. Four suggestions for effective CDW management were provided. They are reducing the amount of CDW, extending the lifespan of buildings, increasing the use of reused or recycled CDW, and promoting proper management of final waste disposal.

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