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Full Length Article

Analysis of construction and demolition waste prediction post-earthquake disasters

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ABSTRACT

The proper management of construction and demolition wastes (CDWs) involves understanding their origins, generation, and efficient collection methods. This is especially crucial in developing countries experiencing rapid urbanization and industrialization, where new construction and the reconstruction of older, lower-quality buildings are common practices. Governmental encouragement for the reconstruction of weak buildings, often due to dangerous conditions or natural disasters like earthquakes, further contributes to the generation of vast amounts of CDWs. In this study, the masses and volumes of CDWs resulting from the Kahramanmaras and Hatay earthquakes that occurred on February 6th, 2023, and the anticipated Istanbul earthquake in Turkiye were estimated. Additionally, the amounts of mineral fraction wastes (MFWs) and scrap iron wastes (SIWs) within these CDWs were calculated, along with their economic values. The quantitative estimations of waste generation for CDW were determined as 396,473,616 tons and 293,684,160 m^3 for Kahramanmaras and Hatay earthquakes, and 393,456,358 tons and 291,449,154 m^3 for the anticipated Istanbul earthquake, respectively. The economic values of recyclable materials (MFWs and SIWs) were calculated as €935,677,734 and €1,268,715,571 for Kahramanmaras and Hatay earthquakes, and €928,557,005 and €1,259,060,346 for Istanbul, respectively.

1. Introduction

Urbanization and industrialization occurring around the world and migration movements, especially towards big cities in recent years, cause changes in the social, economic, and cultural structures of these cities. These changes in cities also create differences in the solid waste amounts and contents. The generation amounts and contents of solid waste generally vary depending on factors such as the development levels of countries, population, construction activities (building construction, demolition activities and materials used in construction, etc.,) and traditions. Among these solid wastes, construction and demolition wastes (CDWs) have a large portion. It has been determined that 36% of the amount of solid waste generated in European countries, 60% in the United States, and 30–40% in China is generated because of construction and demolition activities [1,2]. CDWs are normally generated because of activities such as new building construction, demolition of old buildings, various restoration works, and landscaping. In addition, natural disasters such as floods, earthquakes and landslides result in unexpected and excessive amounts of CDWs. It is estimated that the amount of CDWs generated in 2018 China, UK, and the United States was 3.5 billion tons, 222 million tons and 600 million tons annually, respectively [3]. However, in times of natural disasters, larger amounts of waste are generated. For example, because of the Great Hanshi-Awaji earthquake in Kobe, Japan in 1995, the total amount of waste is estimated to be 15 million tons [4]. This amount means that a landfill that is expected to serve for 10 years will be filled in one year.

Difficulties in the management of CDWs bring about many environmental problems. The control and management of CDWs, which are known to cause various environmental problems due to their can contain hazardous materials such as paint, asbestos etc., is an important issue for human and environmental health, particularly during disasters. Some substances that may be contained in CDWs can cause serious problems for human health. Isocyanates, found in many polyurethane products in buildings, inhaled in high concentrations cause irritation to the eyes, and skin, as well as causing asthma [5]. Asbestos is a substance that has been widely used in the past, is currently prohibited for use, and can be highly damaging to public health. Inhalation of high levels of asbestos fibers causes lung cancer, mesothelioma, and other rare forms

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of cancer. Symptoms of these diseases usually appear about 20–30 years after the first exposure to asbestos [6]. Lead-based materials are frequently used in many areas such as paints, surface coatings, cast iron pipes, plumbing, indoor shooting ranges. The limit value accepted by many countries to minimize exposure to lead-based paints, especially used in homes, varies between 90 and 600 ppm (dry weight). Exposure to lead above specified limits can cause nervous system and kidney damage, stunted growth, and delayed development [7]. Failure to manage disaster waste causes vector-borne diseases such as Dengue fever and malaria to spread through organic waste or water bodies and causes negative consequences such as failure to provide emergency response. Therefore, it is very important to make pre-disaster and post-disaster plans and manage them correctly [4]. In addition, the inadequacy of the landfill capacities used to dispose of these wastes by regularly storing them has also made this issue one of the biggest problems of modern societies [8]. On the other hand, it has been determined that debris (demolition) wastes generated during disasters have significant impacts on post-disaster response and recovery efforts, as well as direct human and environmental impacts. The US Federal Emergency Management Agency (FEMA) in 2007 and Environmental Protection Agency (EPA) in 2019 are identified debris management as a critical issue in natural disaster response. Depending on the nature and magnitude of the disaster, the generation of waste and debris in the affected area can be significant and the amount of CDWs may well exceed normal annual waste amounts. In addition, disaster debris can pose safety threats and impede emergency response, recovery, and reconstruction [9]. Also, one of the main challenges in CDWs management is the lack or weakness of relevant policies, such as green design, waste minimization, the use of recyclable materials, and producer-based responsibility systems. These difficulties hinder the identification, separate collection, and recovery of high economic value materials within CDWs. For example, some countries like Belgium, Czech Republic, Finland, Italy, Spain, and Sweden have compulsory inspections for hazardous CDWs only, while others such as Austria, Denmark, Estonia, Germany, Lithuania, and Portugal lack legislative obligations [1]. In Turkiye, there are regulations such as the Regulation of the Control of Excavation Soil and Construction and Demolition Waste (2004) [10] and the Waste Management Regulation (2015) [11] that outline general rules for reducing excavation soil and CDWs. However, these regulations are not enough for the CDWs management, particularly in terms of promoting sustainable practices and incentivizing the recovery of valuable materials [12].

The wide variety of contents within CDWs leads to discrepancies in their definition and classification, hindering effective waste management [13]. Despite various definitions, the European Commission provides the most general definition of CDWs. According to the European Commission, CDWs are a mixture of different materials, encompassing inert, non-inert, non-hazardous, and hazardous waste, along with a mineral fraction waste (MFWs) such as bricks, tiles, and concrete, which is heavy and easily recyclable but of low value. Additionally, it includes materials with positive market value (metals) or potential value when collected separately in clean fractions (e.g., plastics) [14]. CDWs are heterogeneous and consist of many materials including masonry, concrete, wood, plaster, glass, plastic, excavation soil, and hazardous materials. Sample mass distributions of CDWs content from various literature sources are presented in Fig. 1 [15–19]. As depicted in Fig. 1, the primary mass of CDWs consists of mineral fraction wastes, accounting for 86.71%. The properties of these wastes vary depending on the type of construction and the materials used, such as bricks, concrete, etc. Additionally, they may contain materials such as metals, glass, bitumen, and organic materials [1,20].

Recently, the circular economy model, which emphasizes the use of waste as raw materials instead of the linear economy model that depletes natural resources and increases environmental pollution, has gained preference worldwide for sustainable development. In this approach, the significant volume of CDWs has come to the forefront. The

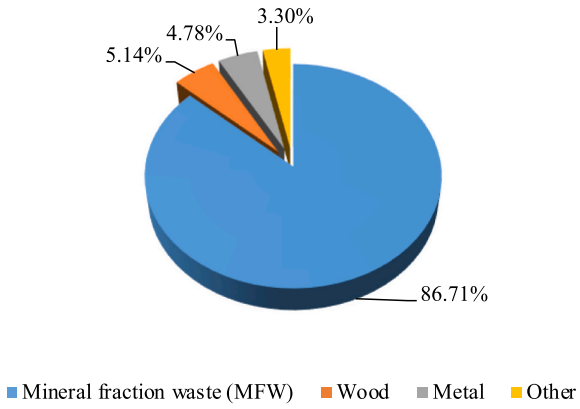

Fig. 1. The sample mass distributions of the contents of CDWs.

fundamental requirement for CDWs recycling is the safe separation and disposal of hazardous materials, along with the management of other reusable wastes through appropriate fractionation methods. Key factors influencing recycling include CDWs separation, reliable material supply and transportation, contamination prevention, and market availability for recycled products [2]. Table 1 provides information on the predominant material fractions of CDWs and their recycling options [21]. Since CDWs primarily consist of inert materials, they can serve as alternative raw materials in various production processes such as road paving, construction foundation filling, pavement and paving stone production, soil stabilization, ground improvement, and ready-mixed concrete production [22]. To establish a circular economy in this field, effective management and a holistic approach are essential to accurately identify and assess the potential of waste materials arising from construction sites to building demolition, which are suitable for reuse, recycling, or recovery. It's crucial to develop plans for evaluating the materials present in the large quantities of CDWs that may arise, especially during natural disasters. In the study conducted by Wu et al. [23] in China, which examined the recycling potential value indices for waste materials, it was stated that the recycling values of metal wastes such as copper are quite high, along with the products obtainable from waste concrete like aggregate in the CDWs. Furthermore, according to calculations by Temelli et al. [22] regarding the earthquake in Kahramanmaras, Turkiye, on February 6th, 2023, it is stated that utilizing CDWs as raw materials can yield an economic gain of approximately 37.5% for mineral fractions and 98.33% for scrap iron from these wastes.

Therefore, the management of CDWs becomes crucial for sustainable development, particularly in their participation in the circular economy, as well as for human and environmental health. In the scientific literature, four approaches are used to estimate the amount of construction and demolition waste:

- Record-Based Accounting Approach: This method is based on field data.
- Material Flow Analysis (MFA) Approach: MFA examines the inflow and outflow of construction materials introduced into service in specific years and provides an overview of material flows throughout the entire construction process.
- Geographic Information System (GIS) Approach: This method uses GIS to track the distribution, production, composition, and variability of solid waste in a specific geographical region throughout the year.
- Weight-Based Construction Area Estimation Method: In this method, waste estimates are made by considering data such as the total area of the project, the number of floors, and the number of residential units in the region [24].

Table 1
Available assessment options for material fractions contained in construction and demolition waste [21].

Type of construction and demolition waste	Available assessment option/technology	Classification according to the Waste Framework Directive
Mineral waste Concrete Bricks Tiles and ceramic Mixed/other Mineral/inert waste	Separation and crushing of mineral waste to produce aggregates to replace sand, gravel, or other low-quality aggregates for road construction.	When used in road construction, recovery (backfilling) can only be reported as recycling in some Member States.
	Concrete waste can be used as a substitute for gravel or crushed rock (e.g., granite) in the production of recycled aggregates for the production of different grades of concrete of the same or lower quality. (Also, the use of the fine fraction still poses some technical and regulatory issues.)	The use of concrete waste in the production of new concrete can be called recycling.
	Old bricks from buildings built before the 1960s can be prepared for reuse if the buildings are selectively dismantled and subjected to a cleaning process. This is still a niche application.	Preparation for reuse
Plastic	If separated by resin type, plastic from CDW can be mechanically granulated for use in the production of new plastic products, although generally of lower quality.	Recycling or other recovery (incineration with energy recovery).
	Plastic can also be recycled as raw material (e.g. recovery of carbon content through pyrolysis or gasification) or incinerated to recover its energy content.	
Metal Mixed metals Ferrous Non- Ferrous	Ferrous metals (iron and steel) and non-ferrous metals (aluminum, zinc, and copper) can be remelted and used to produce new metals.	Recycling
Glass	The glass fraction in CDW can be divided into two categories flat glass and glass used in interior applications. Flat glass can be recycled into new flat glass if it is selectively collected and does not contain any stony material contaminants. Another possibility is recycling into glass containers.	Recycling
Wood	It can be recycled or used for energy recovery. If the wood waste is clean, it can be used in production of particleboard. If contaminated, incineration with energy recovery is usually the preferred solution. In rare cases, wood is also prepared for reuse for structural purposes.	Recycling (if used for particleboard production) or other recovery (incineration with energy recovery). Preparation for reuse in rare cases.
Gypsum	Plaster in CDW is generally in the form of plasterboard. If collected selectively, plasterboards can be converted into new plaster applications; it is used in the production of new plasterboard or in cement production.	Recycling
Insulation	Inorganic insulation materials such as mineral wool are recycled in the brick industry in some countries. Although not widespread, it is possible to recycle stone wool in a closed loop to produce new stone wool. Technologies for closed-loop recycling of glass wool are also under development. Mineral wool produced before 1997 presents a barrier to recycling as it is classified as hazardous waste in some countries and landfilling is still the most common management option for mineral wool waste. Polymer-based insulation materials are mostly landfilled or incinerated, while biobased insulation materials are mostly incinerated or composted if their fire-retardant content is not an issue.	Recycling, other recovery (incineration with energy recovery) or disposal (landfilling)
Paper and cardboard	Paper and cardboard can be recycled and used to produce new paper and cardboard, otherwise they can be incinerated.	Recycling, other recovery (incineration with energy recovery)
Mixed waste, generic	Mixed waste represents an unknown mixture of the waste materials mentioned above. Depending on the processing (e.g. sorting) and the content of this waste fraction, it can be backfilled, recycled, incinerated or landfilled.	Recycling, other recovery (backfilling, incineration with energy recovery), disposal (landfilling)
Hazardous waste (total, excluding hazardous soil and dredging spoil)	Typical contaminants in CDW are heavy metals in paint (e.g., Pb), organics in soft joints, paint (e.g., PCBs, chlorinated paraffins), asbestos fibers in fiber-cement boards and mineral wool classified as hazardous. Therefore, if contaminated, all the waste materials mentioned above could theoretically be classified as hazardous waste and their treatment will depend on the type of waste and the contaminant. Treatment methods can be high temperature incineration, incineration at MSWI with special permits for incineration of hazardous waste, storage in specific cells for hazardous waste or	Other recovery (incineration with energy recovery), disposal (incineration without energy recovery or landfilling)

(continued on next page)

Table 1 (*continued*)

Type of construction and demolition waste	Available assessment option/technology	Classification according to the Waste Framework Directive
	storage in underground storage areas.	

In this study, last method was employed to calculate the waste generated by both the Kahramanmaras and Hatay earthquake on February 6th, 2023 as well as the potential Istanbul earthquake. The waste amount was calculated based on the number of residential units and total housing area. Furthermore, this study calculated the volumetric and mass quantities of CDWs resulting from urgent-severely damaged-collapsed houses (USDCHs), moderately damaged houses (MDHs), and lightly damaged houses (LDHs) due to the Kahramanmaras and Hatay-centered earthquakes, which affected 11 provinces on February 6, 2023. These calculations were performed using different scenarios found in the literature. Additionally, the study estimated the potential CDW generation from the anticipated Istanbul earthquake. This research is significant as it provides CDW estimates for both normal circumstances and disaster scenarios. By offering insights into waste management strategies, it contributes to the circular economy through the sustainable handling of construction and demolition waste.

2. Materials and methods

The aim of this study is to calculate the amounts of CDWs in terms of mass and volume for the Kahramanmaras and Hatay centered earthquakes, which affected 11 provinces in Turkiye on February 6th, 2023. This study also aims that to facilitate mass and volume of CDWs for the anticipated Istanbul Earthquake in the future. The magnitudes of succeeding the Kahramanmaras and Hatay earthquakes were Mw = 7.7 (at 65 s) and Mw = 7.6 (at 45 s). These combined earthquakes produced huge amount of CDWs in the earthquake site. Some of the depicting photographs taken from the earthquake site and the storages area of CDWs were given in Figs. 2 and 3. The CDWs calculations of the earthquake site (for both occurred Kahramanmaras and Hatay Earthquakes, and the anticipated Istanbul Earthquake) were performed using different scenarios, consisting of 14 various values for mass and 7 different values for volume, sourced from the literature. The arithmetic average values provided in the literature were used for the calculation of CDWs amounts. Numerical data for independent residences (including numbers of urgent-severely damaged-collapsed houses (USDCHs), moderately damaged houses (MDHs), and lightly damaged houses (LDHs)) used in the calculation of CDWs in this study were obtained from the reports specified in [25,26]. The total mineral fraction wastes and recyclable mineral fraction (non-hazardous mineral fraction) wastes (RMFWs) of CDWs were used at rates of 86.71% and 59%, respectively, for the calculations in this study. It has reported by Ramos and Marthino [27] that approximately 59% of total CDWs consists of non-hazardous mineral fraction, which includes concrete, brick, tile, and ceramic mixtures that have a high potential for recycling. Additionally, from the calculated CDWs amounts, the quantities of recyclable metal wastes (RMWs) were determined using a rate of 4.784% of the calculated CDWs amounts, as proposed by Ramos and Marthino [27]. RMWs typically include various metals such as Al, Mg, Zn, Fe, Pb, etc. However, this study focuses on evaluating scrap iron wastes (SIWs) for their economic viability and easy recyclable. The quantity of SIWs was determined based on concrete waste data reported by Lauritzen and Jannerup [28], who stated that the maximum amount of concrete obtained from construction demolition waste is approximately 40% by mass. Additionally, Temelli et al. [22] reported that the approximate amount of scrap iron waste in reinforced concrete volume is 30 kg/m^3. These waste rates were utilized in this study for economic analysis. The total weight of CDWs were estimated using the following equation [2,15,16,29]:

$$W = AxWGR \quad (1)$$

where W is total weight of construction, renovation and demolition waste produced in a region (kg, t or m^3), A, area of independent unit house (m^2), WGR is average waste generation per building area during relevant activities (t/m^2, kg/m^2 or m^3/m^2).

In this equation, the area of residence (A) was selected as 150 m^2, which corresponds to the independent unit housing area. The calculations were based on the assumption that the gross housing area (114 m^2 x 1.30 = 148.2 m^2 ≈ 150 m^2) is approximately 150 m^2, considering the addition of common areas (approximately 30%) as indicated by Selcuk and Pasinlioglu [30], where the average housing size is reported as 114 m^2 net area.

3. Results and discussion

The values used in the calculation of mass and volumetric CDWs in this study, as well as those found in the literature, are provided in Table 2. Calculations were performed by averaging the values provided as ranges in the literature. To estimate the potential CDWs amounts for the actual Kahramanmaras and Hatay (February 6th, 2023) earthquakes, as well as the anticipated Istanbul Earthquake, the arithmetic averages of the values presented in Table 2 were utilized. As seen in Table 2, approximately average 1.37 ton/m^2 for the CDWs mass and 1.35 ton/m^3 for the CDWs volume were used in this study. When Table 2 is examined, it is observed that these values show similarities with countries in the Mediterranean and Middle East regions (such as Spain, Portugal, Iran, and Kuwait). Since the types of buildings constructed in Mediterranean regions and the materials used in these buildings are generally similar, they are expected to exhibit the same characteristics. Similarly, in a study conducted by Srour et al. [31], a CDW mass value of 1.73 tons/m^2 was reported for Beirut (Lebanon). These earthquakes affected 11 provinces, resulting in 50,096 deaths, 107,204 injuries, and



(a) (b)

Fig. 2. Photos of the Kahramanmaras and Hatay earthquakes (a: aerial image, b: side view) [25].



(a) (b)

Fig. 3. Photos of the Kahramanmaras and Hatay earthquakes (a: aerial image in Hatay, b: side view in Hatay) [25].

Table 2
The mass, volume, and their averages of CDWs obtained from studies in the literature.

Region/Country	Waste generation (kg/m^2)	Average waste generation (kg/m^2)	Waste generation (kg/m^3)	Average waste generation (kg/m^3)	References
Norway	574.72–1103.25	839.00			[15]
Malaysia		1042.80			[19]
Portugal		1265.00		1470.93	[17]
European Union	195.00–1371.00	783.00		830.60	[33]
Spain		1129.00	1291.76–1542.35	1417.06	[34]
Spain/Galicia		1350.00		700.00	[16]
China		1360.22		1600.00	[23]
Iran		1750.00			[35]
Nepal	1500.00–2740.00	2100.00		1800.00	[36]
China	1461.00–1573.00	1516.00			[18]
Portugal	1050.00–3591.00	2320.50			[37]
Kuwait		1450.00			[2]
China/Shanghai	1192.70–1613.70	1403.20			[38]
USA		910.00			[29]
Turkiye			1610.00–1700.00	1655.00	[39]
Average		**1372.77**		**1353.37**	

damage to 1,929,312 houses out of 2,332,841 residential properties, classified as USDCHs, MDHs, and LDHs (Table 3) according to [25,32].

According to Table 3, it was determined that approximately 90% of the building stock in the earthquake zone consists of residential buildings, with nearly 83% of this building stock being damaged. Therefore, CDWs of these damaged houses were calculated as masses and volumetrically in this study. When Table 3 is analyzed, it is understood that Hatay is the province with the most damaged houses, while Kilis is the province with the least damaged houses. To determine the total CDWs, an independent unit housing area of 150 m^2 was used, as stated in the Material and Methods section. The mass and volumetric-based values based on these data (Table 4) were found separately for the 11 provinces affected by the earthquake. While making these calculations, the values given for the total number of urgently-severely damaged-collapsed houses (518,009 houses), moderately damaged houses (131,576 houses), and lightly damaged houses (1,279,727 houses) damaged by the earthquake were taken from Table 3.

Table 4 presents the mass and volumetric amounts of CDWs generated in the Kahramanmaras and Hatay earthquakes, calculated according to the damage status of the houses, along with the amounts of MFWs, RMWs, concrete waste and SIWs that can be obtained from these values. These calculations were conducted separately for each province affected by the earthquake. Table 4 was primarily divided into three sections. The first section includes calculations for heavily damaged houses that need to be demolished USDCHs, the second section includes calculations for MDHs, and the last section includes calculations for LDHs. Furthermore, the quantities of RMFWs, RMWs, concrete waste, and SIWs determined in each section are presented in Table 4, and summaries of the values from Table 4, along with the economic value for MFWs and SIWs, are provided in Table 5. The economic value of MFWs and SIWs in

Table 3
Total number of buildings, houses and damaged houses in the provinces affected by Kahramanmaras and Hatay earthquakes in Turkiye.

Provinces	Resident (Houses)		Workplace		Public		Other Buildings		Total	Total	Damaged Houses		
	Amount	%	Amount	%	Amount	%	Amount	%	Buildings	Houses	USDCHs	MDHs	LDHs
Adana	404,502	89.67	29,920	6.63	8916	1.98	7779	1.72	451,117	972,561	2952	11,768	71,072
Adiyaman	107,242	89.00	5765	4.78	4370	3.63	3119	2.59	120,496	216,744	56,256	18,715	72,729
Diyarbakir	199,138	88.24	11,412	5.06	11,964	5.30	3165	1.40	225,679	563,295	8602	11,209	113,223
Elazig	106,569	86.14	7221	5.84	2872	2.32	7051	5.70	123,713	292,406	10,156	1522	31,151
Gaziantep	269,212	88.07	22,829	7.47	5480	1.79	8162	2.67	305,683	893,558	29,155	20,251	236,497
Hatay	357,467	87.86	33,511	8.24	10,382	2.55	5489	1.35	406,849	847,380	215,255	25,957	189,317
Kahramanmaras	219,351	90.21	12,358	5.08	6879	2.83	4565	1.88	243,153	481,362	99,326	17,887	161,137
Kilis	33,399	89.51	1526	4.09	1651	4.42	736	1.97	37,312	74,976	2514	1303	27,969
Malatya	159,896	89.33	8370	4.68	6670	3.73	4051	2.26	178,987	345,536	71,519	12,801	107,765
Osmaniye	128,163	89.57	9428	6.59	3105	2.17	2384	1.67	143,080	243,436	16,111	4122	69,466
Sanliurfa	347,902	90.92	18,847	4.93	11,790	3.08	4089	1.07	382,628	718,063	6163	6041	199,401
Total in 11 Provinces	**2,332,841**	**89.08**	**161,187**	**6.16**	**74,079**	**2.83**	**50,590**	**1.93**	**2,618,697**	**5,649,317**	**518,009**	**131,576**	**1,279,727**

Table 4
The masses and volumetrically amount of CDWs for damaged houses and amount of RMFWs and RMWs (House Area: 150 m^2; Unit Mass: 1.37 ton/m^2; Unit Volume 1.35 ton/m^3).

Provinces	USDCHs Total Number	CDWs (tons)	CDWs (m^3)	RMFWs (tons)	RMWs (tons)	Concrete Waste (m^3)	SIWs (tons)
Adana	2952	606,636	449,360	357,915	29,021	179,744	5392
Adiyaman	56,256	11,560,608	8,563,413	6,820,759	553,059	3,425,365	102,761
Diyarbakir	8602	1,767,711	1,309,416	1,042,949	84,567	523,766	15,713
Elazig	10,156	2,087,058	1,545,969	1,231,364	99,845	618,388	18,552
Gaziantep	29,155	5,991,353	4,438,039	3,534,898	286,626	1,775,216	53,256
Hatay	215,255	44,234,903	32,766,594	26,098,592	2,116,198	13,106,638	393,199
Kahramanmaras	99,326	20,411,493	15,119,624	12,042,781	976,486	6,047,850	181,435
Kilis	2514	516,627	382,687	304,810	24,715	153,075	4592
Malatya	71,519	14,697,155	10,886,781	8,671,321	703,112	4,354,712	130,641
Osmaniye	16,111	3,310,811	2,452,452	1,953,378	158,389	980,981	29,429
Sanliurfa	6163	1,266,497	938,146	747,233	60,589	375,258	11,258
Total in 11 Provinces	**518,009**	**106,450,850**	**78,852,481**	**62,806,001**	**5,092,609**	**31,540,992**	**946,230**
Provinces	MDHs Total Number	CDWs (tons)	CDWs (m^3)	RMFWs (tons)	RMWs (tons)	Concrete Waste (m^3)	SIWs(tons)
Adana	11,768	2,418,324	1,791,351	1,426,811	115,693	716,540	21,496
Adiyaman	18,715	3,845,933	2,848,839	2,269,100	183,989	1,139,536	34,186
Diyarbakir	11,209	2,303,450	1,706,259	1,359,035	110,197	682,504	20,475
Elazig	1522	312,771	231,682	184,535	14,963	92,673	2780
Gaziantep	20,251	4,161,581	3,082,652	2,455,332	199,090	1,233,061	36,992
Hatay	25,957	5,334,164	3,951,232	3,147,156	255,186	1,580,493	47,415
Kahramanmaras	17,887	3,675,779	2,722,799	2,168,709	175,849	1,089,120	32,674
Kilis	1303	267,767	198,346	157,982	12,810	79,338	2380
Malatya	12,801	2,630,606	1,948,597	1,552,057	125,848	779,439	23,383
Osmaniye	4122	847,071	627,460	499,772	40,524	250,984	7530
Sanliurfa	6041	1,241,426	919,574	732,441	59,390	367,830	11,035
Total in 11 Provinces	**131,576**	**27,038,868**	**20,028,791**	**15,952,932**	**1,293,539**	**8,011,516**	**240,345**
Provinces	LDHs Total Number	CDWs (tons)	CDWs (m^3)	RMFWs (tons)	RMWs (tons)	Concrete Waste (m^3)	SIWs (tons)
Adana	71,072	14,605,296	10,818,738	8,617,125	698,717	4,327,495	129,825
Adiyaman	72,729	14,945,810	11,070,970	8,818,028	715,008	4,428,388	132,852
Diyarbakir	113,223	23,267,327	17,235,057	13,727,723	1,113,109	6,894,023	206,821
Elazig	31,151	6,401,531	4,741,874	3,776,903	306,249	1,896,750	56,902
Gaziantep	236,497	48,600,134	36,000,099	28,674,079	2,325,030	14,400,040	432,001
Hatay	189,317	38,904,644	28,818,254	22,953,740	1,861,198	11,527,302	345,819
Kahramanmaras	161,137	33,113,654	24,528,632	19,537,056	1,584,157	9,811,453	294,344
Kilis	27,969	5,747,630	4,257,503	3,391,101	274,967	1,703,001	51,090
Malatya	107,765	22,145,708	16,404,228	13,065,967	1,059,451	6,561,691	196,851
Osmaniye	69,466	14,275,263	10,574,269	8,422,405	682,929	4,229,708	126,891
Sanliurfa	199,401	40,976,906	30,353,263	24,176,374	1,960,335	12,141,305	364,239
Total in 11 Provinces	**1,279,727**	**262,983,899**	**194,802,888**	**155,160,500**	**12,581,150**	**77,921,155**	**2,337,635**

Table 5
The summaries of masses and volumetrically amount of CDWs and economic values for MFWs and SIWs.

Damage Types	Total Number of Houses	Total CDWs Amount (tons)	Total CDWs Volume (m^3)	RMFWs (tons)	RMWs (tons)	Concrete Waste (m^3)	SIWs (tons)	MFWs Economic Value (€)	SIWs Economic Value (€)
USDCHs	518,009	106,450,850	78,852,481	62,806,001	5,092,609	31,540,992	946,230	251,224,005	340,642,718
MDHs	131,576	27,038,868	20,028,791	15,952,932	1,293,539	8,011,516	240,345	63,811,728	86,524,378
LDHs	1,279,727	262,983,899	194,802,888	155,160,500	12,581,150	77,921,155	2,337,635	620,642,000	841,548,475
Total	**1,929,312**	**396,473,616**	**293,684,160**	**233,919,433**	**18,967,298**	**117,473,664**	**3,524,210**	**935,677,734**	**1,268,715,571**

Table 5 were determined using 4 €/ton and 360 €/ton that are reported by Temelli et al. [22].

In Fig. 4, the estimated rates of construction and demolition wastes (CDWs, %) generated from urgent-severely, moderately, and lightly damaged houses across all 11 earthquake-affected provinces are presented, respectively. Upon examining Fig. 4, it is determined that Hatay will have the highest amount of waste from urgent-severely and moderately damaged houses compared to other provinces (41.55% and 19.73%, respectively), while Kilis will generate the least (0.49% and 0.99%, respectively). In terms of waste from lightly damaged houses, Gaziantep (18.48%) is expected to produce the highest amount, whereas Kilis (2.19%) will generate the least. These figures can be used by central and local governments to take action or set priorities for CDWs management.

Fig. 5, on the other hand, is expected to facilitate the development of strategies for the sustainable management of CDWs in each of the 11 provinces. This includes recovering/recycling materials and determining reserved areas or establishing landfills for non-recyclable materials. Upon examining Fig. 5, it is observed that in Adana, 83% of the construction and demolition waste generated after the earthquake will originate from urgent and severely damaged houses. Therefore, central and local governments must take immediate action to ensure the sustainable management of this waste. According to Fig. 5, the necessity of implementing existing Disaster and Emergency Action Plans, or urgently developing them if they do not exist, can be emphasized for this province.

USDCHs in the first section of Table 4 are the debris wastes that require urgent decisions for the debris generated in the disaster. Because

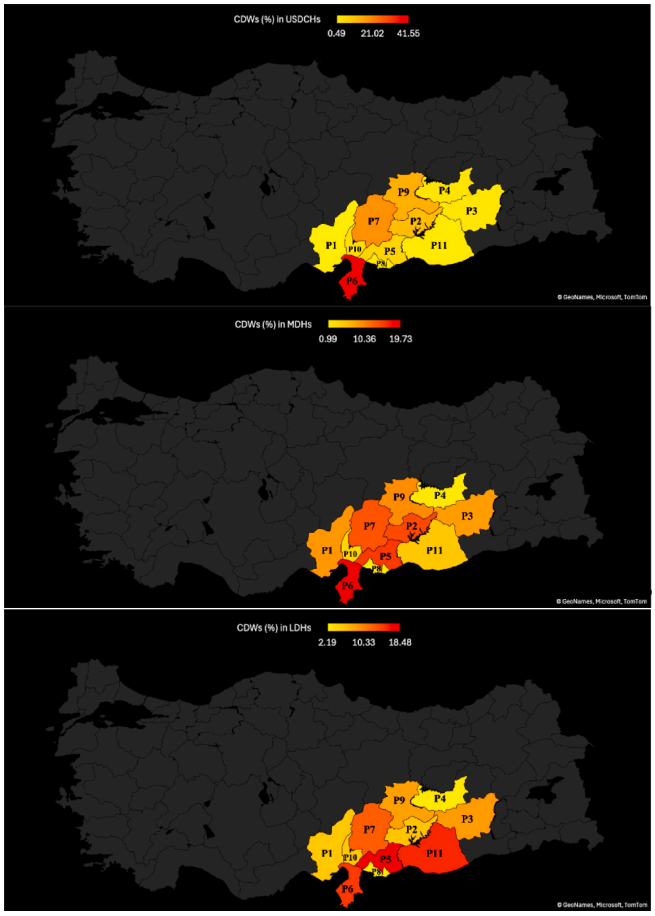

Fig. 4. CDWs (%) in USDCHs, MDHs and LDHs.

these debris may block the transportation routes for first aid and search and rescue activities. In addition, if necessary, safety precautions are not taken around the heavily damaged ones, it may put people's life safety at risk in spontaneous collapses. Therefore, demolition should be carried out within the scope of emergency action plans created administratively for such structures and they should be transported to temporary dumping areas suitable for their quantities as soon as possible within the scope of the plans made in advance. If a temporary storage reserve area is not planned for the storage and separation of large amounts of debris waste immediately after disaster events, this emerges as the biggest obstacle to CDWs waste management in times of disaster. After February 6th, 2023, Kahramanmaras and Hatay earthquakes, it is estimated that approximately 106.5 million tons of CDWs by mass and 78.9 million m^3 by volume will be generated for collapsed, severely damaged and urgently demolished residential buildings. It is estimated that 62.8 million tons of RMFWs, 5 million tons of RMWs, and nearly 950 thousand tons of SIWs which can be recycled without hazardous substances, can be obtained from these wastes. The recycling of these wastes by sorting them in temporary storage areas will be of great benefit to the environment and the economy. For instance, economic values of MFWs and SIWs are 251 million € and 341 million €, respectively (in Table 5).

MDHs are typically structures that require demolition and rebuilding within the first 5 years following a disaster. As these buildings do not necessitate immediate demolition, there is a significant opportunity to conduct essential work on separating reusable and recyclable materials from the waste they generate. This approach enables the maximum recycling of CDWs through sustainable management practices. It is estimated that following the Kahramanmaras and Hatay earthquakes, the total mass of CDWs generated from moderately damaged residential buildings within the first 5 years will be 27 million tons, with a total volume of 20 million m^3. From these wastes, approximately 16 million tons of RMFWs, 1.3 million tons of RMWs, and 240 thousand tons of SIWs without hazardous substances can be recycled. Moreover, the economic values of MFWs and SIWs were calculated to be 64 million € and 87 million €, respectively, for MDHs in this study (in Table 5).

In the case of LDHs discussed in the last section, it is assumed that they will reach the end of their economic life within approximately 20 years, leading to calculations based on the assumption that these buildings will undergo demolition and reconstruction. Consequently, the recycling of CDWs from LDHs, like moderately damaged buildings, will become increasingly important due to global population growth and dwindling natural resources. Given these considerations, it is anticipated that countries will enact changes and improvements in legal legislation pertaining to CDWs recycling to meet building material needs over the next two decades. In the 11 provinces affected by the Kahramanmaras and Hatay earthquakes, it is estimated that 263 million tons of CDWs by mass and 194.8 million m^3 of CDWs by volume will be generated over the next 20 years. From these waste streams, approximately 155.2 million tons of RMFWs, 12.6 million tons of RMWs, and 2.3 million tons of SIWs without hazardous substances can be recycled. Furthermore, the economic values of MFWs and SIWs were calculated to be 621 million € and 842 million €, respectively, for LDHs in this study (in Table 5).

Turkiye is located on the Alpine-Himalayan belt, one of the world's important earthquake zones. There are many active faults in Turkiye due to its complex geological structure and geodynamic location. The Turkiye Active Fault Map was created by the Mineral Research and Exploration General Directorate of Turkiye in 1992. According to the

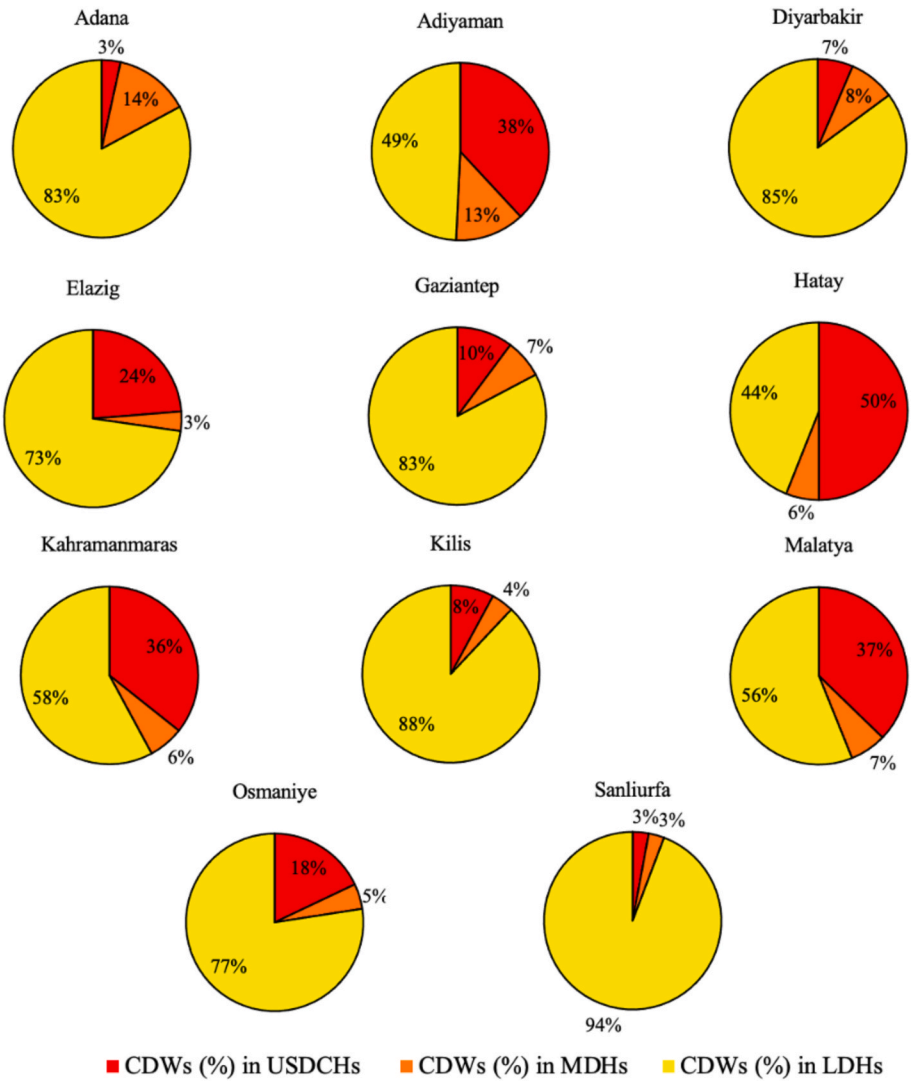

Fig. 5. CDWs (%) in USDCHs, MDHs and LDHs for each province.

Active Fault Map of Turkey, the Northern Anatolian Fault, the Eastern Anatolian Fault, and the Eastern Anatolia, Marmara, and Aegean regions, which cross the country from end to end, are the areas with the highest earthquake risk. The 1999 Izmit Earthquake took place in the Eastern Marmara section of the North Anatolian Fault, and this earthquake affected Istanbul [26]. It is known that many earthquakes have occurred throughout history in Istanbul, an ancient city. Istanbul is the most populous city in Turkiye with a population of approximately 16 million. Therefore, it can be predicted that the effects of an earthquake that may occur in Istanbul will be very large. Unfortunately, according to studies on earthquakes, it is estimated that intense energy has accumulated in the Marmara region of the North Anatolian Fault Line, which includes Istanbul, and this will cause a high-intensity earthquake. In this part of the study, the quantities of CDWs that may arise as a result of the anticipated Istanbul earthquake, as well as the economic values of those that can be recovered from these wastes, were calculated based on the scenario applied in the Kahramanmaras and Hatay earthquakes, 2023 in Turkiye. The findings obtained within the framework of the study are presented in Table 6. Regarding the anticipated Istanbul earthquake, it was estimated in studies conducted within the framework of the "Istanbul Province Possible Earthquake Loss Estimates Updating Project, 2020" by the Istanbul Metropolitan Municipality, Bogazici University, and the Kandilli Observatory and Earthquake Research Institute, Department of Earthquake Engineering, that 57.47% (670,312 buildings) of the buildings in Istanbul would not sustain damage in a scenario earthquake of magnitude Mw = 7.5. On average, it is expected that 25.86% of buildings will incur light damage (301,626 buildings), 12.57% will experience moderate damage (146,552 buildings) and 4.10% will urgent severe damage (47,840 buildings) in the event of an Istanbul earthquake [40]. The total number of buildings analyzed in this report for Istanbul was reported as 1,166,330 (as shown in Table 6). Fig. 6 presents the estimated amounts of Construction and Demolition Waste (CDW) that may result from urgent-severely, moderately, and lightly damaged houses in the expected Istanbul earthquake. According to Fig. 6, the proportions of CDW generated from USDCHs, MDHs, and LDHs are estimated to be 9.65%, 29.55%, and 60.81%, respectively.

The damage sustained by USDCHs in earthquakes is often beyond repair, necessitating their demolition and reconstruction. Similarly, MDHs are also frequently deemed more suitable for demolition and reconstruction rather than repair. According to the scenario outlined in Table 6, it is estimated that approximately 496 thousand buildings will be damaged in the anticipated Istanbul earthquake. Consequently, there is a need to manage the significant amount of CDWs generated by these damaged buildings. It is noted that Istanbul has a total of nearly 4.5 million houses [41]. Utilizing this information, the total number of damaged houses in the anticipated Istanbul earthquake was estimated to be 1,914,629 in this study. Finally, the quantities of CDWs, MFWs, and SIWs were calculated similarly to the scenario observed in the

Table 6
The amount and volume of CDWs that will occur in the anticipated Istanbul Earthquake.

Damage Types	Total Number of Buildings	%	Total Number of Houses	Total CDWs Amount (tons)	Total CDWs Volume (m^3)	RMFWs (tons)	Metal waste (tons)	Concrete Waste (m^3)	SIWs (tons)	RMFWs Economic Value (€)	SIWs Economic Value (€)
USDCHs	47,840	4.10	184,662	37,948,123	28,109,721	22,389,393	1,815,438	11,243,888	337,317	89,557,571	121,433,994
MDHs	146,552	12.57	565,691	116,249,443	86,110,698	68,587,171	5,561,373	34,444,279	1,033,328	274,348,685	371,998,217
LDHs	301,626	25.86	1,164,276	239,258,792	177,228,735	141,162,687	11,446,141	70,891,494	2,126,745	564,650,749	765,628,134
Total Damage	**496,018**	**42.53**	**1,914,629**	**393,456,358**	**291,449,154**	**232,139,251**	**18,822,952**	**116,579,662**	**3,497,390**	**928,557,005**	**1,259,060,346**
Undamaged	670,312	57.47	2,587,404								
Total	1,166,330	100.00	4,502,034								

Fig. 6. CDWs (%) in USDCHs, MDHs and LDHs for Istanbul.

Kahramanmaras and Hatay earthquake, 2023 for Istanbul and are presented in Table 6.

As seen in Table 6, it was estimated that approximately 37.95 million tons of CDWs by mass and 28.11 million m^3 by volume will be generated from USDCH in Istanbul. This study calculated that 22.39 million tons of materials for MFWs and 337.32 thousand tons of SIWs, which can be recycled without hazardous substances, can be obtained from USDCHs of CDWs. If the CDWs of MDHs and LDHs are included in the recyclable total MFWs and SIWs, they would reach 232.14 million tons and 3.5 million tons, respectively. In addition, the economic values of total MFWs and SIWs were determined as 928.56 million € and 1.26 billion €, respectively, for USDCHs, MDHs and LDHs wastes in Istanbul.

4. Conclusion

Unfortunately, earthquakes are disasters that have serious material and moral consequences, especially for countries in earthquake-prone zones like Turkiye. When faced with such natural disasters, another important issue that must be managed and disposed of without posing a risk to the environment and human health is the large amounts of demolition waste. In this study, the amounts of CDWs that may arise from USDCHs, MDHs, and LDHs in the earthquake known as the Kahramanmaras and Hatay earthquake, which affected 11 provinces of Turkiye on February 6th, 2023, and the anticipated Istanbul Earthquake were calculated in terms of mass and volume. The calculation of these mass and volumetric waste amounts for CDWs was carried out by averaging the data found in the literature. Additionally, within the scope of the study, the amounts, and economic values of RMFWs and SIWs included in these wastes were estimated.

In the Kahramanmaras and Hatay earthquakes, Hatay is determined as the province where residences suffered the most damage, and Kilis is determined as the province that suffered the least damage. As a result of this earthquake, it was determined that 51% of the houses in Hatay suffered severe damage. According to the damages (USDCHs, MDHs, and LDHs) in the 11 provinces affected by the earthquake, the masses, and volumes of CDWs were determined as 396,473,616 tons and 293,684,160 m^3, respectively. The materials which they were obtained from CDWs were calculated as 233,919,433 tons for MFWs and 3,524,210 tons for SIWs, respectively, for the Kahramanmaras and Hatay earthquake. The economic values of these recyclable materials (MFWs and SIWs) were calculated as € 935,677,734 and € 1,268,715,571, respectively. If an earthquake with a magnitude of Mw = 7.5 were to occur in Istanbul, it is estimated that 42.53% of the total houses would be affected and categorized as USDCHs, MDHs, and LDHs. According to this scenario, the amount of CDWs were calculated as 393,456,358 tons and 291,449,154 m^3 in this study. In this scenario,

the MFWs and SIWs were determined as 232,139,251 tons and 3,497,390 tons, respectively, for the anticipated Istanbul earthquake. In addition, the economic values of these recyclable materials (RMFWs and SIWs) were calculated as € 928,557,005 and € 1,259,060,346, respectively for Istanbul.

In conclusion, it is deemed that the substantial amount of CDWs, occurring both in normal times and particularly during disasters, are reusable and recyclable wastes possessing high economic value. They should be utilized instead of being stored, ensuring no risk to the environment and human health. The characteristics and quantity of disaster debris are closely linked to the type of disaster that generated the waste. Such waste is likely to overwhelm existing landfill facilities and interfere with other emergency response and recovery activities. Proper segregation of these vast quantities of waste becomes a major governmental task, necessitating costly and complex organization that may take months or even years to complete the cleanup. The objective should be to remove debris swiftly and systematically for disaster waste management that is environmentally sound and financially viable. Recent studies, considering CDWs relevance to Sustainable Development Goals 8, 11, and 12, highlight the importance of prioritizing CDWs recycling. Utilizing CDWs instead of materials requiring substantial raw materials and energy to produce from scratch not only conserves natural resources but also reduces storage volumes, yielding economic benefits.

In order to minimize the environmental risks associated with CDWs and to evaluate it within a sustainable approach under the circular economy framework, studies can be conducted to promptly and effectively implement the following recommendations:

- Providing incentives for the reuse and recycling of construction and demolition waste (such as offering discounts or reductions in energy costs for these activities, allocating land for recycling facilities) and imposing higher disposal fees for those who do not engage in reuse and recycling activities, while enacting legal regulations to impose additional taxes (such as higher tax rates) for the use of unprocessed materials (primary raw materials). Developing marketing strategies to promote the use of waste materials as alternative raw materials (e.g., fostering partnerships between demolition companies and recycling companies for material supply).
- Encouraging companies involved in designing construction and manufacturing construction materials to adopt a zero-waste or minimum waste planning approach and to prioritize the use of recyclable materials.
- Standardizing detailed definitions and classifications of construction and demolition waste contents through national or international studies and promoting the use of common metrics.
- Implementing new technologies suitable for waste reduction strategies during construction activities, raising awareness among professionals in this field, changing societal perceptions regarding construction and demolition waste from being seen as unusable garbage to a potential source of raw materials, and conducting awareness campaigns about the recyclability of these waste materials.
- Conducting scientific calculations before commencing demolition work to estimate fractions such as total, reusable/recyclable, and hazardous waste in terms of mass and volume, and developing sustainable waste management plans by creating separation strategies for recyclable materials.

CRediT authorship contribution statement

Ugur Emre Temelli: Methodology, Data curation, Conceptualization. **Naim Sezgin:** Supervision, Methodology, Formal analysis, Conceptualization. **Bilge Ozdogan Cumali:** Writing – review & editing, Visualization, Investigation. **Semih Nemlioglu:** Writing – review & editing, Methodology.

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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