Environmental Energy and Economic Research 2024 8(1): S074
DOI 10.22097/eeer.2023.390450.1284

Research Article

Life Cycle Assessment of Construction and Demolition Waste Management in Tehran, Iran

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Received: 16 March 2023 /Accepted: 23 July 2023

Abstract
The rapid growth of urbanization, along with the extensive construction of infrastructure and real estate projects, has resulted in higher rates of Construction and Demolition Waste (C&D waste). This condition, combined with the lack or inefficiency of municipal programs to manage C&D waste, has exacerbated urban issues related to C&D waste collection, transportation, and disposal. The purpose of the present study is to apply the Life Cycle Assessment methodology to evaluate the environmental performance of the current management of C&D waste and to identify critical aspects and possible improvement actions in Tehran City. Impact 2002+ performs LCA of the base case (19% recycling), two treatment scenarios. These scenarios included the combined use of landfill, sorting and recycling, and the use of C&D waste in varying percentages. The life cycle inventory analysis was carried out using primary data from field studies and secondary data from the Ecoinvent 3.7 database and the literature. The results demonstrate the benefits of C&D waste recycling in terms of avoided impacts of non-renewable energy, global warming, non-carcinogens, and potentially generated respiratory inorganics and organics from landfill. Thus, our results help ensure that decision-making processes are based on environmental and technical aspects and not just economic and political factors and motivate producers to reduce sources and encourage recyclers and concerned organizations to continuously improve the performance of C&D waste management systems across Iran, and also provide data and support for other LCA studies on C&D waste.
Keywords: Construction and Demolition Waste, Life Cycle Assessment, Waste Management, Openlca, Waste Recycling

Introduction

Today, the construction industry is responsible for generating the largest volume of waste. In general, the waste generated by the construction industry is identified as Construction and Demolition Waste (C&D waste) (Pacheco-Torgal et al., 2020; Yazdanbakhsh, 2018). C&D waste production has increased dramatically around the world with exponential population growth and associated urbanization trends in the 21st century. The overall global expansion of urbanization

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reached 54.3% in 2016 and today the urbanization rate has reached 55% at the global level (Angel, 2012; Aslam et al. 2020). To accommodate the growing population in urban areas, replacing old and low-rise buildings with high-rise buildings generates significant C&D waste (Kim, 2021). C&D waste stream is generated from the construction, demolition, and renovation of buildings, roads, bridges, infrastructures, and clearance or renovation of destroying communities due to disasters such as earthquakes (Cochran et al., 2007; Saca et al., 2017) and it is defined as a mixture of various waste streams, including non-hazardous waste, hazardous waste, and inert waste (Duan et al., 2019).

Evaluating the efficacy of the waste management system has emerged as a crucial issue in the effort to improve C&D waste management performance. Source reduction, recycling, and reuse are the common C&D waste management strategies amidst which recycling has been adopted as a desirable practice worldwide (Li et al., 2022). In the United States, 600 million tons of C&D waste in 2018 was more than double municipal solid waste (MSW) for the same year; more than 75% of these were reused (Rosado et al., 2019). A large proportion (36%) of the total waste in EU countries consists of C&D waste, with most countries having achieved the recycling target of 75% by 2020. Conversely, 40% of MSW generated in urban areas in China is C&D waste, and the country with a 10% recycling rate is lagging behind the national target of 13% by 2020 (Haider et al., 2022).

The production of C&D waste in developing countries is more than in others on account of accelerated urbanization. These countries have established particular standards and directions to manage and limit C&D waste (K et al., 2022). Although various countries focus on C&D waste, few countries could maintain the right balance between C&D waste generation and recycling rate. The effectiveness of policies in many countries can be seen as their limitations; these countries do not implement them properly (Ram et al., 2020).

In Iran, the management of C&D waste is among the fastest-growing concerns due to the fast urbanization and development of the construction industry. Despite that, C&D waste management has not gained proper consideration. Hence, designing a management system for C&D waste is essential. On the other hand, the availability of accurate and reliable data on properties and their current management conditions is a basic requirement for the effective implementation of every waste management plan. The accessible data on the production rate of C&D waste in Iran is sparse. In addition, there is no accessible and precise data that is describing actual C&D waste management and handling practices.

C&D waste could have environmental (e.g. climate change, disabled ecology, energy use and depletion of natural resources, and air, water, and noise pollution), economic (international reputation and tourism losses), public health impacts, and social life (e.g. health hazards, use of public space, spread of pests and effects on occupational safety) (Wang et al., 2018). On a global scale, the construction sector contributes to air pollution (23%), water pollution (40%), climate change (50%), and landfill waste (50%). Most C&D waste components can be recycled or reused, but lack of infrastructure and technological limitations result in the waste generated going to landfill, raising environmental concerns (Quéheille et al., 2022). Rosado et al. identified the following important factors from the published literature that limit C&D waste recycling in most cases: low landfill disposal fees, readily available, inexpensive aggregate, poor quality of recycled aggregate, and ineffective sorting practices at source (Rosado et al., 2019).

Life Cycle Assessment is considered one of the best tools to obtain a reliable quantification of the environmental impacts of C&D waste management systems (Butera et al., 2015; Ferronato et al., 2021). In general, the LCA studies about C&D waste have been developed to verify the environmental impacts of end-of-life buildings (Zampori et al., 2016; Vitale et al., 2017), to compare the benefits of recycled aggregates versus natural aggregates (Faleschini et al., 2016), to determine the environmental burdens of recycling processes (Coelho & de Brito, 2012; Lockrey et al., 2018), and to analyze the environmental performance of C&D waste management systems (Borghi et al., 2018; Butera et al., 2015; Yazdanbakhsh, 2018).

This study aims to assess the environmental impacts associated with the current C&D waste management system from a life cycle perspective, analyzing alternative management scenarios to identify possible improvements to the system. The Waste Management Organization of Tehran Municipality (WMOTM) and private companies are responsible for C&D waste management from the collection of C&D waste in the city to transfer to recycling facilities and landfills. Primary data and information were collected through local authorities (waste management organizations and private agencies), direct investigations to CDW recycling plants and quarries, and related research. There are few LCA studies about C&D waste management at this level in Iran, the applied methodology can be used as a starting point for future studies on this field.

Material and Methods

Study Area and Data Collection

To perform a detailed Life Cycle Impact Assessment (LCIA) of a C&D waste management system, defining the study area boundaries is commonly the first step. The study area selected in the present study is Tehran, the capital of Iran. Tehran is located at 35.7219° N 51.3347° E with an area of 730 km^2. Nowadays, independent contractors collect most of the C&D waste generated from all types of C&D waste from construction and demolition sites. Figure 1 shows the city districts and the location of recycling and disposal facilities.

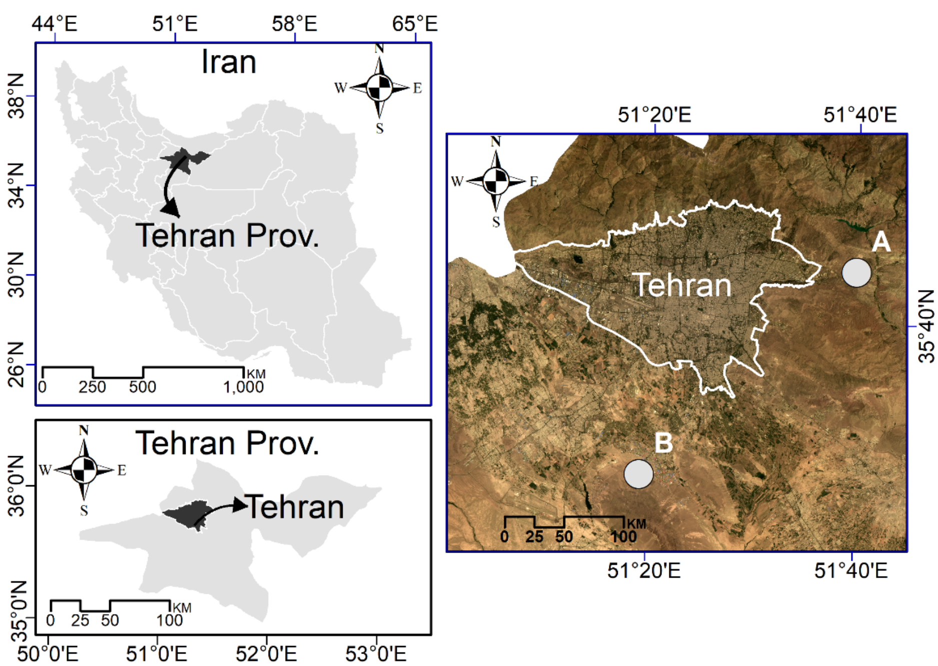

Figure 1. Study area and the place of recycling and disposal facilities (A: Tehran construction waste disposal, B: Aradkooh waste processing plant)

The municipalities in Iran are facing several challenges related to the current practices of C&D waste management from the absence of suitable regulation for the control of the subcontractors who are responsible for collecting the generated C&D waste from source to landfill, recycling, and disposal processes. The official management infrastructures (Tehran Construction waste Disposal (TCD)) used by the municipality comprise sorting areas, C&D waste recycling facilities, and/or inert landfill. Tehran construction waste disposal is the main recycling facility and landfill in Iran that is located 40 km northeast of the city center. The entry waste stream into the center is 21000 tons per day, while the daily average generation of C&D waste is 34000 tons. Presently, the TCD is recycling only 6600 tons of C&D waste generated in a day and produces different types of aggregates from the collected mineral C&D waste based on their sizes (recycling 85% of the entry C&D waste). These aggregates will be used for backfilling, pipes backfilling, construction of concrete blocks, manufacturing of hollow and solid bricks, concrete for infrastructure installations, sub-base layers, etc. In addition, for the management of non-mineral C&D waste fraction, it is necessary the use different configurations of recycling facilities, as well as sanitary landfills. Daily, around 3000 tons of C&D waste on average are transferred to the Aradkooh waste processing plant which is used as liners in sanitary landfills. This plant is located 38 km south of the city center.

Life Cycle assessment

Life cycle assessment is a commonly used approach to evaluating the environmental performance of a product or system. It considers the environmental impact of a product system from cradle to grave, examining the life cycle stages from raw material extraction, manufacturing, transportation through use, and end-of-life treatment to final disposal (McDougall et al., 2008). Based on the contribution of the Society for Environmental Toxicology and Chemistry (SETAC), the International Standards Organization (ISO) has further developed the ISO 14040 Life Cycle Assessment (LCA) series. According to ISO 14040, the phases of an LCA consist of four phases: (i) goal and scope definition, (ii) life cycle inventory (LCI), (iii) life cycle impact assessment (LCIA), and, (iv) interpretation. However, the ISO standards are defined in rather vague language, making it difficult to assess whether an LCA has been prepared by the standard.

Goal and Scope Definition

The most critical methodological choices, assumptions, and limitations should be clearly described in the first phase. These include the functional unit, initial system boundaries, criteria for inclusion of inputs and outputs, and scenario setting (Duran et al., 2006). The overall goal of this study is to evaluate the environmental performance of the C&D waste management in Tehran City, considering the current (base case scenario) and some alternative scenarios.

The functional unit has been defined as the management of 34,000 tons of C&D waste per day that is obtained through reports of the Waste Management Organization of Tehran Municipality (Pasmandiran site, 2021). Only a few studies have carried out C&D waste characterization, by using different methodologies; the samples are collected in different sites, resulting in variations in the composition. Table 1 presents the composition and quantities of the C&D waste in Tehran City.

Scenario analysis is employed to determine optimal C&D waste management scenarios. There are two categories to set up scenarios in previous C&D waste LCA studies, which are: (a) making the comparison among current practice situations, targets in C&D waste management plan, ideal prospects (i.e., Maximum Recycling, Maximum Energy Recovery), and worse case (i.e., Landfill) and (b) making the comparison among different treatment facility/system (Chau et al., 2017; Wu et al., 2015).

Table 1. Composition and quantities of C&D waste in Tehran (Asgari et al., 2017; Rouhi Broujeni et al., 2016).

C&D waste composition	Percent	Amount (Tonnes per day)
Concrete	19	6460
Bricks	18	6120
Mix sand and cement	30	10200
Soil and Stone	14	4760
Gypsum	4.2	1428
Asphalt	1.3	442
Tiles	9.8	3332
Metals	0.7	238
Wood	0.5	170
Glass	1	340
Paperboard	1	340
Plastic	0.5	170
Total	100	34000

The base case scenario is the current C&D waste management in Tehran city. In this scenario, 19.4% of generated C&D waste is recycled and the rest of C&D waste is sent to landfills (open dump and inert landfill).

The alternative management scenarios (Table 2) consider the crucial role of the recycling of the mineral and non-mineral fractions. In the first alternative scenario (Treatment scenario 1), the whole of the mineral fraction is recycled and produces aggregates in TCD. The rate of recycling is assumed 85%. In Treatment Scenario 2, the whole C&D waste stream is sent to TCD and recycled the same as in the previous scenario. Choosing scenarios based on technology and energy consumption for recycling both mineral and non-mineral fractions of C&D waste was critical.

Table 2. Construction and demolition waste management scenarios for Tehran City

Scenario	Recycling Rate (%)	Direct waste to Landfill (%)	Reject to Landfill (%)	Overall waste to Landfill (%)
BCS: Base case scenario	19.4	80.6	2.9	83.5
TS1: Treatment scenario 1	96.3	3.7	14.5	18.2
TS2: Treatment scenario 2	100	0	15	15

The system boundaries include all treatment processes, starting from waste entering the management system until when it leaves the system as an emission (solid, liquid, or gaseous) or as a secondary material (Borghi et al., 2018). Cases of multi-functionality were solved by expanding the system boundaries to include avoided primary productions due to material recovery from waste (Finnveden et al., 2009). The system includes the following activities/processes (Figure 2):

- Unloading, moving, and uploading C&D waste in construction sites and recycling facilities/landfills;
- C&D waste recycling, including sorting and aggregates production
- C&D waste disposal;
- Natural aggregates (NAs) avoided production;

- Primary non-mineral fraction avoided production;
- Transportation of C&D waste to recycling facilities/landfills.

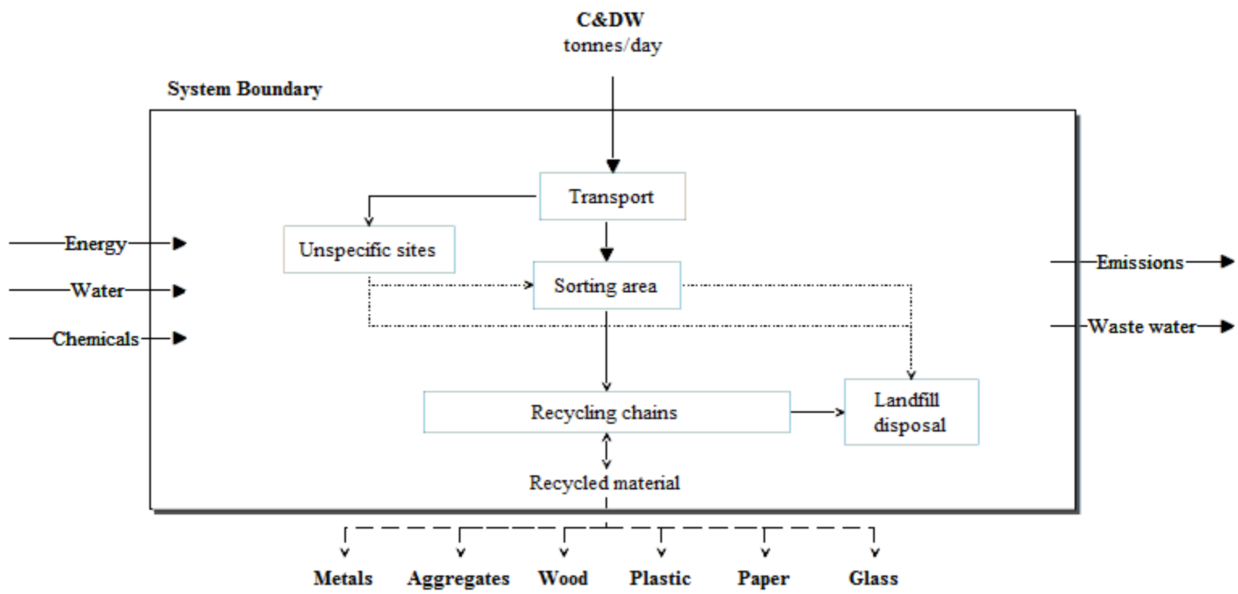

Figure 2. System boundary for the C&D waste management system considered in this study

The present study used the latest version of OpenLCA 1.11.0 software. The software is based on an attributional approach that describes all the potential environmental impacts over the life cycle of a system. This methodology uses historical, fact-based, measurable data of known uncertainty and includes all the processes that significantly contribute to the system under study (Haider et al., 2022). The primary data used to develop the life cycle inventory were obtained from the MOMRA website, through personal visits to SIRC, and the published reports. Impact 2002 + v.2.15 evaluated the life cycle impacts of C&D waste using midpoint and endpoint categories.

Life Cycle Inventory

The most demanding task in performing an LCA is data collection. Although much secondary data is available in literature or database like *ecoinvent*, it is usually found that at least a few processes or materials are unavailable (Dahlbo et al., 2015).

In this study, most of the direct burdens for the life cycle inventory have been obtained from official reports or technical visits to infrastructures. The remaining direct burdens, indirect burdens related to materials and energy required for C&D waste management operations, and avoided burdens have been obtained from the literature and *ecoinvent* v.3.7 databases.

The allocation problem in the LCA model has been avoided by using the system expansion method (also called ‘‘avoided burden” or ‘‘substitution”), in which the life cycle inventory of the processes or products replaced by the obtained co-products is subtracted from the analyzed system (Doka, 2003).

The inventory of transportation stages has been developed based on primary data about the distances, and direct and indirect burdens of transportation have been calculated considering the emissions from the process ‘‘passenger car” and ‘‘lorry 16–32 tons (EURO 4)”, according to *ecoinvent*. Primary data about the diesel and lubricating oil consumption by the wheel loaders have been obtained, and direct and indirect burdens related to these consumptions are derived from *ecoinvent*.

The direct and indirect burdens from inert landfilling are related to energy use for operation, as leachate emissions have not been considered. This assumption appears reasonable since the waste material disposed of in this type of landfill has low pollutant content and is chemically inert to a large extent (Di Maria et al., 2018). On the other hand, the emissions from open dumps of a non-mineral fraction have been considered based on *ecoinvent* v.3.7.

In this work, due to the lack of monitoring and data related to the amount of emissions of pollutants in air, water, and soil, based on the climate of Tehran, it was extracted from the *ecoinvent* v.3.7 database.

The inventory of mineral fraction of C&D waste sorting and recycling has been elaborated based on primary data obtained in the recycling. The indirect and direct burdens related to Iran's electricity production mix and diesel consumptions derived from Ecoinvent v.3.7. Plastics, steel, wood, and glass recycling have been developed based on secondary data from the literature and *ecoinvent* v.3.7 (Ye et al. 2017).

Impact assessment

According to ISO 14040/44, a life cycle impact assessment is designed to understand and evaluate the magnitude and significance of potential environmental impacts of the system. It usually contains essential elements (i.e., classification and characterization) and optional elements (i.e., normalization, ranking, grouping, and weighting) (ISO 14040/ 44). Previous C&D waste LCA studies usually select one well-developed impact assessment method or a refined method, rather than create impact assessment methodologies.

Impact 2002 + v.2.15, as described in, has been used to evaluate the environmental impacts related to LCA. Past studies also suggested the use of Impact 2002 + v.2.15 in the absence of local data (Blengini & Garbarino, 2010). Due to the lack of C&D waste data for LCIA in Iran, different waste management scenarios (described in the following section) were compared and analyzed using midpoint and endpoint categories. Single score midpoint categories were carcinogens, non-carcinogens, respiratory inorganics, respiratory organics, terrestrial ecotoxicity, terrestrial acid/nutria, land occupation, global warming, and non-renewable energy, whereas the single score endpoint categories included natural resources, climate change, ecosystem quality, and human health (Arena et al., 2015).

Results and Discussion

In the base case scenario, Table 3 shows that non-renewable energy accounted for 98.8%, whereas the contribution of other midpoint categories is under 1% (global warming accounted for 0.6%, terrestrial ecotoxicity accounted for 0.4%, land occupation accounted for 0.06%, and mineral extraction accounted for 0.06%). Although selecting the European context seems rational due to the neighboring geographical location of Iran, the results presented in Table 3 might differ from the actual results for the study area.

Table 3 also presents the percentage contributions of endpoint categories. It can be seen in the table that natural resources have the highest contribution (98.96%), followed by climate change (0.6%) and ecosystem quality (0.47%) impacts, whereas human health has the least contribution to environmental impacts amongst the midpoint categories.

Table 3. Percentage contribution of environmental impact categories for BCS.

Midpoint Category	Endpoint Category	Unit	Environmental Impact Contribution %	
			Midpoint	Endpoint
Carcinogens	Human health	kg C2H3Cl eq	< 0.01	< 0.01
Non-carcinogens		kg C2H3Cl eq	< 0.01	
Respiratory inorganics		kg PM2.5 eq	< 0.01	
Respiratory organics		kg C2H4 eq	< 0.01	
Terrestrial ecotoxicity	Ecosystem quality	kg TEG soil	0.4	0.47
Terrestrial acid/nutri		kg SO2 eq	0.01	
Land occupation		m2org.arable	0.06	
Global warming	Climate change	kg CO2 eq	0.6	0.6
Non-renewable energy	Natural resources	MJ primary	98.9	98.96
Mineral extraction		MJ surplus	0.06	

The analysis of endpoint categories demonstrates that transportation of C&D waste and mixed sand and cement landfilling make the major contribution to human health, whereas, in the ecosystem quality, inert landfill and transportation have the major portion. Like the two mentioned categories, in the climate change impact, transportation plays the main role. The last category is natural resources which its main share belongs to C&D waste landfilling.

To improve the C&D waste management in Tehran City, two alternative treatment scenarios were developed in the present study to increase the percentage of recycling. The characterization results of all scenarios are detailed in Table 4. Throughout the analysis, negative values denote environmental savings.

Table 4. Characterization of impacts for all scenarios

Impact category	BCS	TS1	TS2	Unit
Carcinogens	2.42E+03	5.44E+03	2.94E+03	kg C2H3Cl eq
Global warming	3.21E+05	1.65E+05	-3.47E+05	kg CO2 eq
Land occupation	2.15E+04	-2.49E+03	-6.44E+03	m2org.arable
Mineral extraction	1.94E+03	1.14E+03	5.20E+02	MJ surplus
Non-carcinogens	4.96E+03	7.64E+02	-1.47E+04	kg C2H3Cl eq
Non-renewable energy	3.39E+06	4.43E+05	2.78E+05	MJ primary
Ozone layer depletion	3.61E-02	2.57E-04	-3.20E-03	kg CFC-11 eq
Respiratory inorganics	6.49E+02	-8.98E+02	-9.30E+02	kg PM2.5 eq
Respiratory organics	8.56E+01	-6.46E+01	-7.61E+01	kg C2H4 eq
Terrestrial acid/nutri	4.51E+03	-1.51E+04	-1.59E+04	kg SO2 eq
Terrestrial ecotoxicity	1.80E+07	8.92E+06	7.59E+06	kg TEG soil

To evaluate different scenarios, the LCIA results of the scenarios were compared with the BCS in the analysis. Figure 3 shows the results concerning the three main phases of the C&D waste management system for the selected impact categories of the Impact 2002+ characterization. The considerable importance of C&D waste recycling is emphasized, which not only refers to the avoidance of waste from landfills but mainly to the avoided impacts from recovered materials.

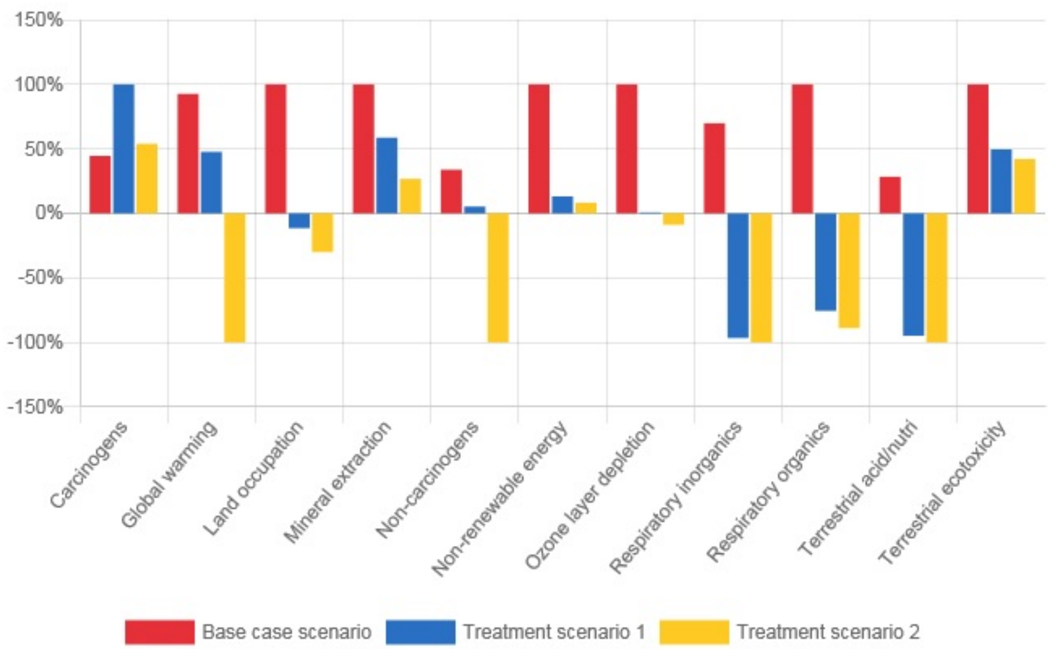

Figure 3. Results of the comparison between BCS and treatment scenarios by using normalized factors for Europe of Impact 2002+ methodology

In all of the impact categories, except for carcinogens, environmental impacts have decreased. The comparison between BCS and TS1 for each impact category demonstrates that environmental benefits have been changed in the following details: global warming (45%), land occupation (112%), Mineral extraction (41%), non-carcinogens (29%), non-renewable energy (87%), ozone layer depletion (99%), respiratory inorganics (165%), respiratory organics (176%), terrestrial acid/nutria (123%), and terrestrial ecotoxicity (51%). In the same way, comparison between BCS and TS2 shows the environmental benefits: global warming (193%), land occupation (130%), Mineral extraction (73%), non-carcinogens (134%), non-renewable energy (92%), ozone layer depletion (109%), respiratory inorganics (170%), respiratory organics (189%), terrestrial acid/nutria (128%), and terrestrial ecotoxicity (58%). The environmental burdens of the carcinogens category increased by 55% and 9% in TS1 and TS2, respectively.

As of 2022, the Materials Recovery Facility received 6600 tons of C&D waste collected from Tehran City, representing 19.4% of the total (34000 tons) waste generated. The recycled material, including mixed sand and cement, concrete blocks, tiles, asphalt, and clay brick, accounts for 78.1% of the C&D waste collected. Recycled aggregate recovered from this significant fraction of C&D waste can play an essential role in meeting primary aggregate needs for infrastructure development, e.g. roads and concrete to replacement.

The remaining non-recycled waste, consisting of soil (mud, clay, and stone), reinforced concert, plaster and drywall, steel (bars, rods, and brackets), gypsum, paperboard, plastic, and wood, accounts for a small portion of the total C&D waste generated. Based on the existing recycling capacity, the recycled material is separated from the C&D waste. The sorted recycling material then runs through the picking station, with magnets separating the remaining steel content and the density separator removing small and fine parts that are not suitable for aggregate formation. This waste accounts for about 15% of the recycled waste and joins the non-recycled waste at the landfill.

The treatment scenarios improve the existing recycling rate from 19.4% to 100% with the same process chain, in which 10% of fines are landfilled. The results show that by recycling the non-mineral fraction of C&D waste, in the category of human health, environmental impacts are greatly diminished by reducing emissions. Also, global warming is greatly reduced by recycling the non-mineral sector, by preventing raw materials extraction and manufacturing

Recycled aggregate from 100% recycling can replace 10% to 100% virgin aggregate in several manufacturing and construction activities. The largest size of aggregate produced is 20-50 mm which can replace up to 100% of the new aggregate required for all backfill applications such as raising site level, retaining site structure, and filling excavated areas. The same aggregates can also replace the unused aggregates needed to cover pipe networks. The next size of aggregate, 10-20 mm, can replace the new aggregate in the manufacture of interior walls, the new aggregate in concrete for the manufacture of manholes for sanitary and stormwater drainage systems, virgin aggregate for the manufacture of hollow bricks for use in non-structural walls and virgin aggregate for the containment of water and sewage works. The next smaller size, 5-10 mm, made from recycled aggregate can replace up to 100% of the new aggregate used in road construction sub-bases. Finally, the smallest size (0.5mm) aggregates can replace 100% of virgin aggregates in the construction of temporary farm-to-market roads and as bedding for water pipes and plumbing, and storm sewers.

Conclusion

Large cities in Middle Eastern countries are producing a large quantity of C&D waste. Being one of the largest cities and the capital of Iran, Tehran is currently producing over 34000 tons per day from 22 municipalities covering all the important regions of the city. To meet the sustainable development goals, the entire city is going through extensive construction and demolition activities. The present study assessed the potential environmental impacts of the current (and planned) C&D waste management system of Tehran City using Impact 2002+ LCIA methodology. The assessment results revealed that C&D waste recycling significantly avoided the potential impacts of non-renewable energy, global warming, non-carcinogens, respiratory inorganics, and Respiratory organics midpoint environmental impact categories generated by landfilling. The study also found that mineral-fraction recycling significantly avoided the human health impacts of “non-carcinogens” and “respiratory inorganics” generated by landfilling. In addition to the direct avoided impacts of landfilling, conversion of C&D waste into different sized (0–50 mm) aggregates can replace 10–100% virgin aggregates in several construction activities, including backfilling applications, encasement and bedding of water mains and sanitary and storm sewers, manufacturing of walls and manholes, non-load bearing walls, and encasement of water and sewerage linear assets. These results encourage the WMOTM in Tehran City to actively participate in source segregation, handling, and storage of C&D waste to enhance the effectiveness of recycling materials. With the support of the municipalities, recycling facilities can effectively improve the existing 19.4% recycling rate to 100%. To achieve the environmental benefits of C&D waste reuse and recycling, the outcomes of the present study need to be validated at each development stage (capacity enhancement, process change, and practices) of the existing and possible facility.

Acknowledgment
The authors would like to express their deepest gratitude to Dr. Hassan Hoveidi, for approving this study as well as for his support and guidance throughout the study.

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