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Challenges of earthquake waste management: A systematic literature review

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Abstract

Background: Earthquake-generated waste poses serious threats to public health and the environment, making disaster waste management a critical issue. Achieving integrated management requires a thorough understanding of the challenges posed by earthquake-related waste. To address this, the present systematic literature review was conducted to identify and classify the key obstacles in earthquake waste management.

Methods: This systematic review analyzed articles published between 2014 and November 2024. Searches were conducted in the Scopus, PubMed, and Web of Science databases using keywords such as "waste management," "solid waste," "trash," "debris," "garbage," and "earthquake," along with their Persian equivalents. All stages of the review adhered to the PRISMA checklist guidelines, and the quality of the selected studies was assessed using the Mixed Methods Appraisal Tool (MMAT).

Results: An initial pool of 693 articles was identified after database searches and duplicate removal. Following systematic screening of titles, abstracts, and full texts, and applying inclusion and exclusion criteria, 18 articles were selected for data extraction and quality assessment. From the full-text analysis of these documents, the challenges of earthquake waste management were categorized into eight groups: (1) strategic management, (2) laws and budgets, (3) health and environmental threats, (4) education and human resources, (5) infrastructure and equipment, (6) technical and specialized aspects, (7) executive management, and (8) information and resources.

Conclusion: Identifying the challenges of earthquake waste management provides essential insights for managers and policymakers, enabling the adoption of a comprehensive approach that improves decision-making and strategic planning to address waste-related issues in post-earthquake scenarios.

Keywords: Disasters, Earthquakes, Waste management, Solid waste

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Introduction

Disasters, whether natural or man-made, occur daily across the globe and leave profound impacts on human societies, the environment, the economy, and social structures. Among these disasters, earthquakes are among the most destructive natural events, often generating vast amounts of waste (1,2). This earthquake-generated waste poses significant threats to public health and the environment, affecting community well-being both directly and indirectly (3). While not all earthquake-related damage is limited to environmental and human health risks, the associated social, economic, and political challenges underscore the critical need for effective waste management during such events. Proper waste management plays a pivotal role in mitigating damages, protecting public health, and ensuring sustainable recovery efforts (4).

In recent years, disaster waste management (DWM) has emerged as a fundamental aspect of disaster risk reduction (5). Both the Hyogo Framework for Action (2005) and the

Sendai Framework for Disaster Risk Reduction emphasize the critical role of waste management in mitigating the impacts of disasters. The Hyogo Framework incorporates waste management into its risk-reduction strategy for post-earthquake recovery planning. At the same time, the Sendai Framework highlights it as a key objective in broader disaster risk reduction efforts (6,7).

Comprehensive and integrated waste management is a critical prerequisite in the aftermath of earthquakes. If this process is not effectively implemented during the early stages of relief efforts, it can lead to escalating issues and costly, complex challenges during the reconstruction phase (8,9). Unfortunately, inadequate attention to this issue has often led to waste management processes being poorly executed or entirely neglected, leaving them insufficient to meet the extensive needs of earthquake-affected populations (10,11).

Addressing the challenges and overcoming the inefficiencies in earthquake waste management requires a comprehensive understanding of the existing barriers to establish an integrated and effective system. Analyzing deficiencies and identifying obstacles in earthquake waste management is crucial, as recognizing these weaknesses and contributing factors can lead to the development of systematic solutions to manage earthquake-generated waste effectively.

Given the limited number of studies adopting a systematic review approach to address the challenges of earthquake waste management, this research aimed to identify and analyze the barriers and issues associated with managing waste in earthquake conditions.

Materials and methods

Eligibility criteria

This study is a systematic review registered in PROSPERO under the code CRD42020190088. No restrictions were applied regarding the type or methodology of the included studies, nor regarding the publication date. The selected studies specifically focus on waste management in the context of earthquakes and disasters.

Data Sources

The search was conducted in the Scopus, Web of Science, and PubMed databases to identify articles published between 2014 and November 2024, with no restrictions applied.

Search Strategy

This study aimed to answer the research question, "What are the challenges and obstacles of waste management in disasters?" To achieve this, keywords from related articles were initially identified and used. Subsequently, related terms were extracted from the Medical Subject Headings (MeSH) in PubMed. Experts were also consulted to identify additional relevant keywords. Finally, the extracted keywords were combined using the AND and OR syntax operators to formulate a search query in the PubMed database. After conducting an initial pilot search in PubMed, the syntax was adjusted for use in the Scopus and Web of Science databases. The finalized search strategy for each database is presented in Table 1.

Study selection

The identified studies were first imported into EndNote (version X8) software, where duplicate entries were removed. The remaining articles' titles and abstracts were screened, and relevant studies were selected. Subsequently, two researchers (S.K. and M.F.) independently reviewed the full texts of the remaining articles to select the most relevant articles for the study. Any disagreements between the two researchers were resolved through group discussions and consensus. If disagreements persisted, a third researcher's opinion and guidance were sought.

To ensure that no relevant studies were overlooked, the references of the selected articles were also reviewed. Additionally, key journals on the research topic were searched in the Scopus database for relevant articles. However, no additional articles met the inclusion criteria at the final selection stage. After finalizing the selection, the chosen articles were reviewed and approved by all authors of this study.

Synthesis of results

This study investigated the challenges and problems associated with waste management during earthquakes. Following a comprehensive analysis of issues related to managing earthquake-induced waste, the findings were compiled and organized in an Excel spreadsheet. The extracted data included details such as research titles and authors, year of publication, country of study, research methodology, sample size and characteristics, and key findings on the challenges and obstacles to waste management during earthquakes. Subsequently,

Table 1. Search strategies in databases

Database	Search Keywords
PubMed	(((((((waste management [Title/Abstract])) OR (solid waste[Title/Abstract])) OR (garbage[Title/Abstract])) OR (trash[Title/Abstract])) OR (debris[Title/Abstract])) AND (earthquake[Title/Abstract])) OR (sesim*[Title/Abstract])
ISI Web of Science	(TS = (waste management) OR TS = (solid waste) OR TS = (debris) OR TS = (garbage) OR TS = (trash)) AND (TS = (earthquake) OR TS = (seism*))
Scopus	(TITLE-ABS-KEY (waste AND management) OR TITLE-ABS-KEY (debris) OR TITLE-ABS-KEY (garbage) OR TITLE-ABS-KEY (trash) OR TITLE-ABS-KEY (solid AND waste) AND TITLE-ABS-KEY (earthquake) OR TITLE-ABS-KEY (seism*))

all identified management challenges and obstacles were categorized through a group discussion involving the research authors. Duplicate obstacles were merged, while similar obstacles were grouped. Any disagreements about the naming or classification of factors were resolved through further group discussion.

Risk of bias in individual studies

Critically assessing article quality is an essential step in systematic reviews, and various tools are available to support this. However, these tools are typically tailored to specific research designs, making it challenging to evaluate systematic reviews that include studies employing diverse methodologies. Given the methodological diversity in the studies included in this research, and following extensive reviews, it was necessary to adopt a tool capable of assessing studies with different approaches simultaneously. For this purpose, the Mixed Methods Appraisal Tool (MMAT), developed at McGill University, was used to evaluate concurrently quantitative, qualitative, and mixed-methods studies.

Results

Following a comprehensive database search and the removal of duplicate records, 693 articles were imported into EndNote software (version X8) for preliminary review. A systematic screening of the articles was then performed following the PRISMA flow diagram (Figure 1), which involved evaluating the titles, abstracts, and full texts of each article. Ultimately, 18 articles met the inclusion criteria. Their characteristics, along with the extracted findings, are summarized in Table 2.

Features of articles

The reviewed studies were conducted in 13 countries, including New Zealand (1), Italy (12,13), the United States (17), Japan (15,26), Turkey (16,25), China (14), Mexico (18), Iran (5,8,23) Australia (19), Nepal (4,27), Haiti (21), Malaysia (22), and Ecuador (24). Among the analyzed studies, four employed mixed methods, three used evaluation approaches, three used analytical methods, two adopted modeling techniques, two were qualitative studies, two were review-based, one used a quantitative (survey-based) approach, and one followed a comparative

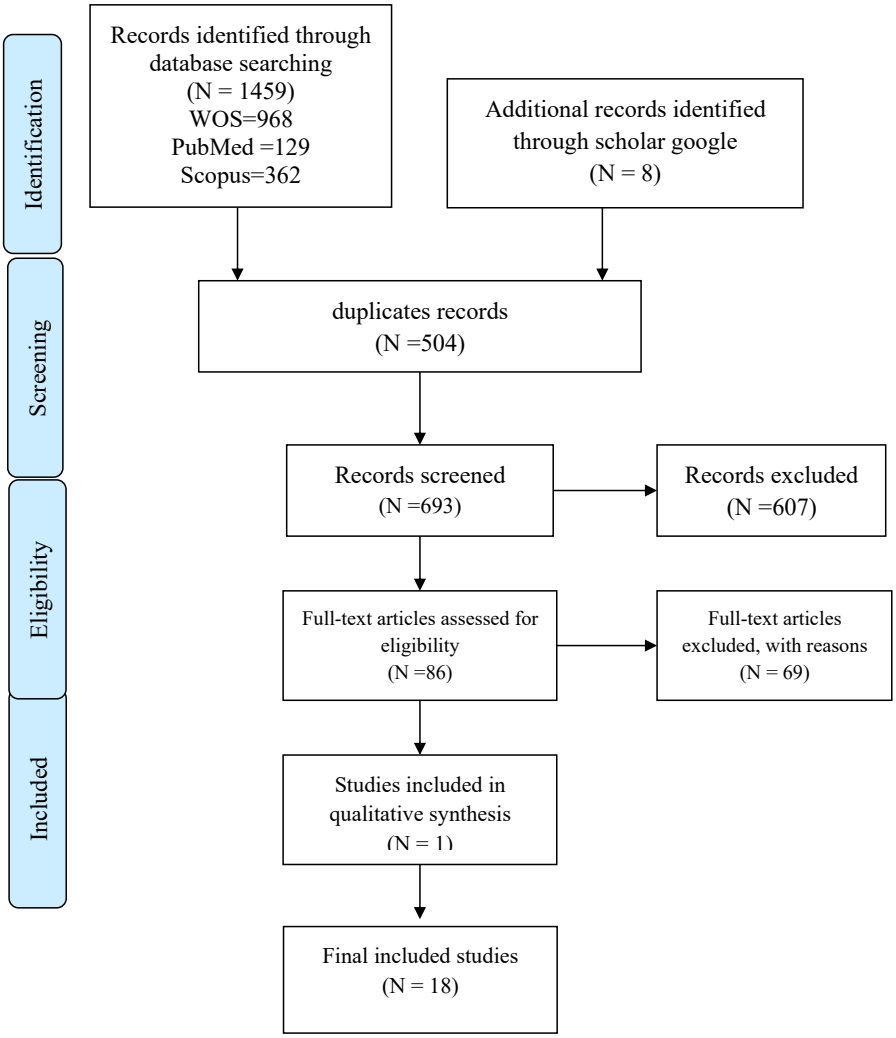

Figure 1. PRISMA flow chart of article selection

Table 2. The characteristics of the conducted studies and the extracted results

Authors / year/ country	Title	methodology	Study Objective	Key Findings
Domingo et al, 2017, New Zealand (1)	Canterbury earthquake Construction and demolition waste management Issues and Improvement suggestions	Semi-structured interviews and questionnaires.	Examining C&D waste management after earthquakes.	1-Effectiveness of the "Pick and Go" strategy: This strategy effectively directed debris straight to the end-use market and was highly efficient
Amato et al, 2019, Italy (12)	Strategies of disaster waste management after an earthquake: A sustainability assessment	**Research Method**: Environmental and economic assessment **Tools:** Carbon impact estimation and economic analysis of options. **Analysis:** Comparison of options based on costs and environmental effects.	To determine the best waste management options to reduce environmental and economic impacts.	1-Pre-treatment and advanced waste treatment are environmentally beneficial. 2-Simple treatment and transporting waste to the treatment site is the most cost-effective option. 3-Advanced treatment increases costs, and its environmental impacts may have long-term economic consequences.
Basti, 2018, Italy (13)	Sustainable Management of Debris from The L'Aquila Earthquake: Environmental Strategies and Impact Assessment	**Research Method:** Environmental impact assessment using LCA (Life Cycle Assessment) methodology and technical feasibility analysis. **Tools:** Evaluation of environmental impacts and feasibility of different waste management options. **Analysis**: Comparison of strategies based on their environmental impacts and technical feasibility.	Evaluation of different debris and waste management options, including centralized and decentralized management.	1-The shortest distance option is ideal for debris management when a strong recycling network exists, reducing emissions and creating local job opportunities.
Zhang et al, 2016, China (14)	Retrospection-Simulation-Revision: Approach to the Analysis of the Composition and Characteristics of Medical Waste at a Disaster Relief Site	**Research method:** Retrospective-simulation-revision for analysing medical waste. **Tools:** 35 medical relief records from the Wenchuan earthquake. **Analysis**: Combining retrospective analysis and simulation with revision of waste composition.	Analysing the composition of medical waste in disaster relief to enhance management.	1- The analysis of the composition and density of medical waste emphasizes the importance of accurate recording and storage of medical records for effective waste management and environmental assessment in disaster-affected areas.
Saffarzadeh et al, 2017, Japan (15)	Tasks and problems involved in the handling of disaster waste upon April 2016 Kumamoto Earthquake, Japan	This study combines field surveys and drone technology for high-resolution imaging and rapid estimation of disaster waste.	The aim of this study is to estimate and manage disaster waste quickly following the earthquake, using temporary storage facilities and drone technology.	1- Temporary storage facilities were constructed near the affected areas for the segregation and processing of waste materials such as wood, metal, glass, and concrete. 2- Drone technology was used for high-resolution imaging and rapid estimation of disaster waste. 3- The study emphasized the importance of storage and waste processing facilities for effective waste management. 4- The volume of generated waste was assessed.
Onana, et al, 2015, Turkey (16)	An evolutionary multi-objective optimization approach to disaster waste management	This study uses the NSGA-II optimization model to reduce costs and hazards from hazardous waste and to manage disaster waste in an integrated manner.	The aim of this study is to design a framework for the sustainable management of disaster waste.	1-Reduction of construction resource needs: Recycling and reusing materials from debris reduces the need for new resources for construction. 2-Sustainable waste management: Temporary storage facilities for processing recyclable materials are proposed based on international guidelines. 3-multi-objective optimization model: The model addresses cost reduction and hazardous waste risks. 4-Implementation of the model in Istanbul: Istanbul has been chosen as a case study for implementing the proposed framework.

Table 2. Continued.

Authors / year/ country	Title	methodology	Study Objective	Key Findings
Trivedi et al, 2015, USA (17)	Analysis of key factors for waste management in humanitarian response: An Interpretive Structural Modelling approach	This research uses Interpretive Structural Modelling (ISM) to examine the relationships and impact of various factors in disaster waste management.	The aim of the study is to identify key factors affecting disaster waste management and improve the efficiency of crisis response.	1-Geography, geology, and the type of disaster have a direct impact on the speed of debris management. 2- These factors are uncontrollable, but they should be considered in waste management planning for vulnerable areas. 3- Donors, the disaster-affected population, and local and regional management can significantly contribute to the successful implementation of disaster waste management programs.
Hernández-Padilla et al, 2021, Mexico (18)	Earthquake Waste Management, Is It Possible in Developing Countries? Case Study: 2017 Mexico City Seism	This study examines earthquake waste data, analyses waste management capacity through interviews, and evaluates the legal framework and public policies for disaster waste management.	Designing a framework for earthquake waste management in developing countries.	1- The weight of earthquake debris was estimated. 2- The estimated weight of household items per collapsed dwelling was determined. 3- The political problems and challenges related to disaster waste management in developing countries were analysed.
Askarizadeh et al, 2015, Iran (5)	Management of post-earthquake construction debris in Tehran Metropolitan	This study uses network analysis to determine the shortest routes for debris transportation and estimates the debris volume, as well as the required machinery and manpower.	The aim of this study is to estimate the earthquake debris volume and calculate the resources required for debris management.	1- Examination of the debris volume generated based on different earthquake magnitudes 2- Determination of the disposal site area for debris management 3- Activities such as preparedness, emergency operations, and reconstruction can reduce earthquake-induced damages.
Cheng et al, 2018, Australia (19)	Reliability analysis for disaster waste management systems	This study uses the first-order reliability method and event tree analysis to assess system reliability and failure modes through an artificial case study with three disaster scales.	The aim of this study is to propose a two-stage framework for estimating the reliability and analysing failure modes of a disaster waste management system.	1- The results of the case study assist decision-makers in determining route priorities and identifying potential failure modes.
Sakai et al, 2019, Nepal (20)	Field study of disaster waste management and disposal status of debris after Gorkha Earthquake in Kathmandu, Nepal	This research included field visits, interactions with local communities, meetings with officials involved in debris management, and the use of published reports.	The aim of this study is to examine disaster waste management and estimate the volume of debris generated and managed.	1- Of the 3.23 million tons of debris generated, only 1.07 million tons were managed within two years, 2-with 0.63 million tons openly dumped and 0.44 million tons recycled or reused. About 2.17 million tons remain unmanaged, 3- with open dumping as the main disposal method.
Raila et al, 2017, Haiti (21)	Healthcare waste management during disasters and its effects on climate change: Lessons from 2010 earthquake and cholera tragedies in Haiti	This study analysed 60 months of incinerated healthcare waste data using Pearson correlation, linear regression, and time series models.	The aim of this study is to examine the climate change risks associated with healthcare waste disposal during and after the 2010 earthquake and cholera disasters.	1-There was a weak correlation between the quantities of healthcare waste incinerated and the time of occurrence of natural disasters. 2-Linear regression analysis showed a linear trend in the data with fluctuations, with a peak in healthcare waste incineration in 2012. 3-The peak in waste incineration occurred two years after the 2010 disasters. 4-The Haitian government had no data on healthcare waste disposal and used open burning methods. 5-There is a need to strengthen green healthcare waste management to mitigate the impacts of climate change.

Table 2. Continued.

Authors / year/ country	Title	methodology	Study Objective	Key Findings
Zawaw et al, 2015, Malaysia (22)	important criteria for managing disaster waste In Malaysia	qualitative research design involving comprising of journal review, previous case study and semi-structured interviews	The aim of this study is to explore the possibility of integrating waste management into disaster management guidelines in Malaysia.	1-Identification of key criteria related to disaster waste management in Malaysia. 2-The results attracted the attention of researchers and policymakers in waste management. 3-Essential elements were provided for the development of disaster waste management policies.
Pradhananga et al, 2015, Nepal (4)	Disaster Waste Management Challenges in Nepal: Health Impacts and the Need for Safe Practices	This study employed a case study method and surveyed 103 local officials and stakeholders in Nepal, including workers, volunteers, and professionals from governmental and non-governmental organizations.	The identification and documentation of health and safety issues in post-disaster waste management activities, particularly following the earthquake, have been conducted.	1-Health issues in disaster waste management have increased, particularly for individuals lacking safety training and proper personal protective equipment. 2-40% of participants experienced at least one health problem. 3-Lack of training and preparedness, along with insufficient local community involvement, have exacerbated
Kazemi et al, 2023, Iran (23)	The challenges of strategic management of the wastage produced due to earthquake in Kermanshah and Varzaghan-Ahar: A qualitative study	This study was conducted using a qualitative content analysis approach and purposive sampling. The data were analysed in the form of 418 codes, 97 subcategories, 33 categories, and 8 main categories based on a deep analysis of participants' experiences and perceptions.	The aim of this study is to examine the challenges of strategic management of earthquake-induced waste.	1-optimal use of the opinions provided by managers, researchers, and experts interested in the field of waste management for the development of guidelines and national regulations for the management of healthcare waste in an earthquake
Rodriguez Rios et al, 2022, Ecuador (24)	Appropriate management of earthquake generated waste: Lessons from the 2016 earthquake in Ecuador	This study collected its data through questionnaires provided to 22 recycling businesses and statistical information from public and private institutions.	The analysis focuses on the problems caused by the lack of pre-disaster planning for waste management, which led to challenges in decision-making, material recycling, and waste disposal.	1- The waste management limitations after the earthquake included a lack of landfill sites and recycling facilities. 2- In the first month following the earthquake, only 20% of the waste was recycled or reused.
Kasapoglu et al, 2024, Türkiy (25)	Disaster waste management process: The case of February 6 earthquake	This study used document analysis, reports, and case studies, and examined waste management regulations in Turkey and the European Union.	This study aims to emphasize the importance of disaster waste management and provide improvement recommendations by comparing Turkey's regulations with European Union directives.	1-In the earthquake-affected area of Kahramanmaraş, there were no waste storage or sorting facilities. 2- the existing laws lacked sufficient details for disaster waste management. 3-The waste management process was not properly implemented and contradicted existing regulations. 5-Global experiences could help improve this process, and recommendations were made to strengthen laws and improve waste management implementation to prevent similar issues in future earthquakes.
Marchesini et al, 2023, Japan (26)	Organising disaster waste management as a critical infrastructure	A comparative study of countries such as France, New Zealand, Japan, and the United States, which have experience in disaster management.	Examining the necessity of considering disaster waste management as a vital activity and its impact on organization and planning.	1-the generation of massive amounts of waste by disasters and the negative impacts of inefficient management. 2-The lack of recognition of waste management as a critical infrastructure in many countries. 3-The functional similarities of waste management with other urban systems. 4-The potential for waste management to adopt emergency planning practices from vital urban systems. 5-The proposal to recognize waste management as a critical activity to enhance disaster preparedness and response.

methodology.

A review of findings from various studies revealed that the challenges of waste management during earthquakes stem from multiple factors. Based on previous research, these challenges can be classified into eight main categories, as outlined in Figure 2. These categories include 1) strategic management, 2) laws, regulations, and budget, 3) health and environmental threats, 4) education and human resources, 5) infrastructure and equipment, 6) technical and specialized challenges, 7) executive management, and 8) information and resources.

Strategic management challenges include the absence or incompleteness of waste management policies, organizational limitations, unclear operational plans, unclear roles and responsibilities at all levels, and insufficient integration of waste management into national earthquake response plans (18,28). The study findings emphasize poor management and inadequate planning as critical issues in post-earthquake waste management (8). One study specifically identified the lack of clear policies as a fundamental challenge (29). Additionally, an analysis of multiple earthquakes highlighted the insufficient prioritization of waste management as a significant obstacle (19).

A key challenge in managing earthquake-generated waste is the lack of comprehensive and transparent regulations in this field. The absence of specific, practical laws, particularly during post-earthquake reconstruction, leads to problems such as improper waste disposal, poor coordination among responsible agencies, and significant threats to the environment and public health. Legal gaps, including the lack of detailed standards for the separation, recycling, and disposal of construction waste and hazardous waste, as well as ineffective regulatory mechanisms, greatly diminish the efficiency of waste management. These shortcomings not only exacerbate environmental impacts but also create significant obstacles to reconstruction, delaying disaster recovery efforts. Findings from various studies indicate that the absence of well-developed laws can make waste management a significant challenge (17,30). Developing comprehensive, clear regulations in this area is essential to promoting environmental sustainability and ensuring effective crisis management.

Insufficient budget allocation for waste management following earthquakes is a significant factor in the failure to address the environmental and health crises they cause. The lack of adequate financial resources for infrastructure, waste collection and disposal equipment, and specialized personnel training significantly disrupts recovery and cleanup efforts. Additionally, limited funding for the research and development of advanced waste management technologies hinders the implementation of effective, sustainable solutions. These financial shortcomings can lead to the accumulation of waste, increased costs, and heightened risks to public health and the environment.

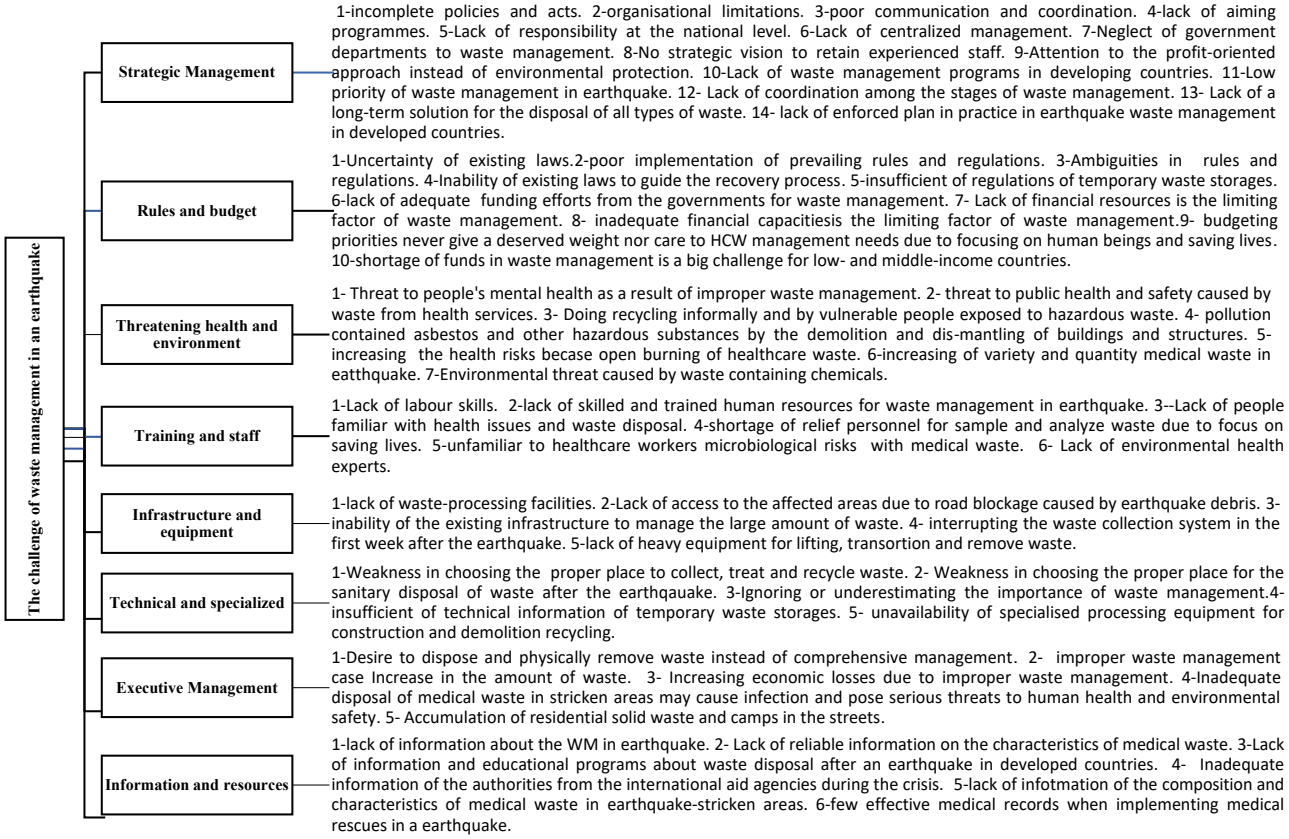

Figure 2. Grouping the challenges of waste management in an earthquake

A review of various studies highlights that neglecting proper financial allocation makes waste management a significant challenge (17,18).

Threats to health and the environment have been identified as significant challenges in waste management following earthquakes. These include risks to mental health within affected communities, threats to life and the possibility of fatalities, and the impacts of improper and unregulated waste disposal (18). Additionally, earthquake-related construction pollution, such as asbestos contamination (16), and the demolition of buildings, along with the release of chemicals from damaged structures and storage facilities in residential areas, further exacerbate these challenges. Such threats often lead authorities to deprioritize waste management during disaster response efforts (31).

Training and human resources are critical challenges in waste management, particularly during crises such as earthquakes. The absence of trained and specialized personnel in such situations can severely disrupt waste management processes (24,32). These disruptions include delays in waste collection, separation, transportation, and safe disposal, which significantly increase environmental and health risks.

Scientific evidence highlights several key issues, including the shortage of specialists to manage specific types of waste, such as hazardous chemicals, and the lack of effective training programs to enhance personnel skills. These deficiencies not only reduce organizations' capacity to respond swiftly and effectively but also prolong cleanup efforts and escalate costs (14,33). Additionally, the lack of proper procedures and adherence to scientific standards in waste management further undermines the system's efficiency. This challenge is particularly pronounced in the disposal of hazardous chemicals after earthquakes, where the shortage of specialized personnel poses a serious and ongoing threat (18).

To mitigate the environmental and social impacts of earthquakes, providing adequate facilities, enhancing infrastructures, and developing strategic waste management plans are fundamental priorities. These measures can improve the efficiency of reconstruction efforts, minimize adverse consequences, and accelerate the recovery process in earthquake-affected areas. However, in inefficiently managed scenarios, infrastructure and equipment themselves often become part of the waste management challenges. Critical issues include insufficient waste-disposal facilities, road blockages caused by earthquake debris that restrict access to affected areas, and the existing infrastructure's inability to handle the large volumes of waste generated. Additional challenges include disruptions in waste collection systems during the initial days and weeks following the disaster, shortages of heavy machinery for moving, transporting, and safely disposing of waste, and the absence of standardized spaces for temporary storage and disposal. These deficiencies exacerbate the crisis, making waste management a central challenge in disaster response and the reconstruction of earthquake-affected areas (17,21,33).

Technical and specialized issues are significant challenges in waste management following earthquakes. These include weaknesses in selecting appropriate locations for sanitary waste disposal (13), underestimating the importance of waste management, and insufficient technical knowledge of temporary waste storage facilities. Other notable challenges include the lack of specialized equipment for processing construction debris and recycling demolition materials (18), as well as the absence of methodological approaches for accurately estimating waste composition and quantity. Difficulties in determining the exact volume of construction waste further compound the problem. The findings indicate that one key factor contributing to ineffective waste management is insufficient technical capacity to estimate and manage waste accurately (27).

Executive management is a key challenge in waste management, as highlighted by various studies. The accumulation of waste in streets is often seen as a clear indicator of poor management, with potentially severe environmental and social consequences. Major issues in this area include inefficiencies in waste cleanup operations, delays in the cleanup process, and increased associated costs (19,34,35).

Another factor contributing to ineffective waste management is the lack of information management and related resources. Many waste management methods used during earthquakes have been ineffective due to the absence of up-to-date information and evidence-based practices informed by past earthquake experiences. Studies highlight that the lack of reliable data on waste characteristics and the absence of comprehensive training programs for post-earthquake waste disposal remain critical challenges, even in developed countries (18). Furthermore, insufficient knowledge among officials in international relief agencies during crises has compounded the complexity and inefficiency of waste management (17,21).

Discussion

This study aimed to examine the challenges of waste management during earthquakes by analyzing existing research. The results of these studies were categorized into eight distinct groups.

One of the fundamental factors contributing to inefficient waste management is weak strategic management. Strategic management involves a set of activities and approaches that organizations use to define and achieve their objectives. However, several deficiencies can significantly undermine its effectiveness (36). Inadequate policies and weak organizational communication create ambiguity and reduce operational capacity, posing serious

challenges for waste management (1). The absence of comprehensive policies impedes accurate budgeting, resource allocation, and the development of an appropriate organizational structure for waste management, particularly during earthquakes (37). Incomplete policies and unclear organizational directives create uncertainty in goal-setting and implementation, reducing focus and internal coordination. Additionally, poor organizational communication disrupts the flow of information and strategic knowledge, impairs coordination between units, and makes it more difficult to achieve objectives.

To address these challenges, it is essential to develop appropriate policies, enforce relevant regulations, and adopt strategic approaches (32,38). For instance, previous studies, including research on strategic management during the Haiti earthquake, emphasize the importance of timing and program efficiency as key principles in planning (39). Improving strategic waste management during earthquakes requires integrated planning frameworks (40), comprehensive regulations, simulation exercises, investments in infrastructure and modern equipment, and training programs for specialized personnel (41). Incorporating advanced technologies such as artificial intelligence and GIS (42), strengthening monitoring and evaluation systems, and leveraging international experiences can further enhance waste management processes. These measures will help governments overcome challenges such as weak planning, resource shortages, and the lack of specialized personnel, ultimately improving the efficiency of waste management in earthquake-affected areas.

Effective regulations are a fundamental requirement for proper waste management during crises such as earthquakes. The absence of clear laws or the inefficiency of existing regulations often leads to confusion and inefficiencies in waste management (43). Many organizations lack preventive plans to address disasters like earthquakes or floods, relying instead on implementing relevant laws and guidelines only after such events occur (17). This reactive approach results in chaos during waste disposal, a lack of transparency in managing hazardous waste, and unclear delineation of roles and responsibilities. For optimal management of hazardous waste, precise regulations detailing disposal, transportation, and storage methods are essential. Without such laws, illegal disposal or mismanagement can occur, causing significant harm to the environment, public health, and individual safety (44). Additionally, a lack of awareness and proper training among individuals often leads to improper waste segregation, incorrect disposal practices, and the neglect of critical principles such as waste reduction, recycling, and reuse (45).

Insufficient funding is another significant challenge in post-earthquake waste management. Earthquakes typically generate large volumes of waste and debris, requiring substantial financial resources for collection, transportation, processing, and disposal (46). Allocating adequate funds for public education and awareness, as well as for providing the necessary equipment and infrastructure, is crucial in addressing this issue (20). Without sufficient funding, even well-established regulations become ineffective. Governments and local authorities must therefore prioritize allocating financial resources to waste management to prevent the environmental and human consequences of improper waste handling (6). In particular, allocating appropriate and sustainable budgets for managing earthquake-related waste is essential—especially in developing countries—to mitigate these challenges effectively.

Earthquakes and other natural or man-made disasters generate significant amounts of natural and hazardous waste, posing serious threats to public health and the environment. Waste produced by earthquakes, particularly when contaminated by chemicals and hazardous materials, can directly harm human health. For instance, contaminated waste can pollute water, soil, and air, increasing the risk of disease outbreaks (13). In addition to causing environmental damage, these issues create complex challenges for waste management and safe disposal. Among these challenges are the rise in chemical pollutants, microbial contamination, and diseases such as asbestosis—major concerns that demand special attention during crisis management processes (2). Various review studies underscore the critical role of health concerns in waste management, findings that align with recent research in this field (47). This highlights the urgent need for improved management strategies and preventive planning to mitigate the negative impacts of crises on both the environment and public health.

One of the main challenges in waste management is the shortage of specialized human resources (48). Trained and skilled personnel play a critical role in planning and implementing effective waste management strategies after crises such as earthquakes (5). By leveraging their technical and managerial expertise, these individuals can enhance waste management processes and help reduce damage (49). Moreover, they are instrumental in the early stages of crisis assessment by identifying weaknesses in existing systems, selecting appropriate waste management methods, and supporting local communities during the crisis.

A review study on waste management challenges in natural disasters highlights the importance of specialized human resources in this field, a finding consistent with the present study (50). Conversely, weak strategic management often fails to allocate resources for human resource training and does not provide adequate programs to develop specialists or raise staff awareness in waste management (50,51). This educational gap can lead to increased operational errors and inefficiency in

responding to crises.

Overall, ineffective strategic management—stemming from a lack of long-term vision and policy cohesion—exacerbates other challenges, such as shortages in laws, financial resources, and trained personnel (52). To address these issues, it is crucial to develop and implement practical, continuous training programs, recruit and employ specialized personnel, and establish necessary training facilities in operational environments (8,52,53). These measures can significantly improve waste management efficiency during crises, reducing environmental and public health risks.

Advanced equipment and reliable infrastructure, along with appropriate machinery for handling solid waste, are essential for optimal waste management. Efficient equipment enables swift, effective waste management, thereby reducing the amount that harms the environment (54). To address challenges related to equipment shortages, implementing a comprehensive risk management program and allocating adequate financial resources are crucial strategies (16,17,48). One study highlights the importance of sufficient financial resources for addressing challenges in designing flood and drought prediction models. These findings can also be applied to the need to invest in infrastructure and equipment for waste management (50). Adequate investment in this area not only improves waste management efficiency but also helps mitigate the environmental and public health risks associated with crises (55).

Technical and specialized challenges are among the most significant barriers to effective waste management following an earthquake, affecting the efficiency and effectiveness of this process. One major challenge is the difficulty in selecting appropriate sites for sanitary waste disposal, which can have harmful consequences for the environment and public health (46). Additionally, neglecting the critical role of waste management and lacking sufficient technical knowledge about temporary waste storage—especially during crises—are key obstacles (56).

The absence of specialized equipment for processing construction waste and recycling debris (57), combined with the lack of methodological approaches for accurately estimating and managing waste quantities, further complicates this process (58,59). Another significant issue is the challenge of accurately determining the volume of construction waste, due to the lack of clear standards and effective monitoring systems (60). These challenges, supported by findings in related studies, underscore the importance of developing technical knowledge, acquiring specialized equipment, and establishing standardized methods for waste management (61,62). Moreover, the implementation of temporary and incomplete waste management measures—alongside delays or failures in completing reconstruction efforts—exacerbates these difficulties. This highlights the urgent need for a comprehensive and systematic approach to waste management in crises. Strengthening planning, enhancing coordination among relevant institutions, and allocating adequate resources can play a crucial role in addressing these challenges and improving the overall efficiency of waste management efforts.

Weak executive management during crises such as earthquakes can exacerbate existing challenges and create additional problems, compounding the primary crisis. In such situations, making quick and effective decisions is essential. Executive management plays a critical role in this process by providing accurate information and correctly assessing the situation, which facilitates optimal decision-making for waste management (63). One common issue in post-earthquake waste management is the reliance on temporary decision-making to address immediate challenges, which often results in secondary problems (46,64). Adopting a comprehensive and strategic waste management approach can help mitigate these complications. Furthermore, executive management can strengthen communication and coordination among various community institutions, enabling the sharing of resources and expertise, thereby enhancing disaster response and waste management efficiency (65).

The study's findings also highlight planning as a fundamental principle of waste management—a responsibility that lies with management teams—and further align with the present study's conclusions (10). These challenges underscore the urgent need to improve technical knowledge, adopt scientific and standardized methods, and employ advanced equipment for recycling and optimal waste disposal (66). Implementing these measures can significantly improve waste management practices and reduce the environmental and social impacts of natural disasters.

One of the fundamental challenges in post-earthquake waste management is the lack of accurate information and reliable resources for planning and implementing management actions. The collection and precise analysis of data—such as the quantity and type of waste, the extent of earthquake damage, and a proper assessment of crisis conditions—are essential for effective waste management (12,26). Without comprehensive information and data-driven awareness, secondary damages can occur, further complicating the crisis.

Data-driven management and a thorough understanding of the incident are critical for minimizing adverse effects and improving crisis management. However, evidence indicates that this approach is often not applied in earthquake waste management. This finding aligns with related studies that emphasize the need to strengthen information systems and educational frameworks in this field (55,67). Addressing these gaps by fostering better data collection and analysis practices can significantly

enhance the effectiveness of waste management during crises.

Addressing these challenges requires creating comprehensive databases, developing specialized training programs, and incorporating lessons learned from past experiences to improve the management of information and resources during critical times. Implementing these measures can significantly enhance the efficiency of waste management processes while reducing the environmental and human consequences of crises.

Conclusion

The findings of this study highlight the significant and multifaceted challenges in managing earthquake-generated waste. Key constraints include the absence of comprehensive, coherent policies for planning and field operations, unclear regulations, insufficient allocation of financial resources, poor information management and documentation, and inadequate training and deployment of specialized personnel. In addition, infrastructural and technical issues—such as improper site selection for waste disposal—serve as significant barriers to effective waste management during crises. These challenges can lead to severe negative impacts on the environment and public health, further complicating the recovery process.

To address these issues, developing and enforcing clear, comprehensive regulations, optimally allocating financial resources, strengthening infrastructures, and training specialized personnel are crucial. Strategic and comprehensive planning, informed by lessons learned from past crises and supported by up-to-date data, is essential for mitigating environmental and health consequences and for accelerating post-crisis recovery. Prioritizing these strategies is vital to achieving sustainable waste management during earthquakes and enhancing community resilience against future disasters.

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Competing interests

The authors declare that there is no conflict of interest.

Ethical issues

In this article, the authors have addressed all ethical aspects of data collection and certify that the manuscript represents their original work. They affirm that all data gathered for the study are accurately presented in the manuscript and that no part of the data has been or will be published elsewhere. This article is derived from a PhD thesis approved by the Ethics Committee of Yazd University of Medical Sciences (ethical code: IR.SSU.SPH.REC.1399.096).

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