Mapping healthcare waste management research: Past evolution, current challenges, and future perspectives towards a circular economy transition

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Abstract:

Improper healthcare waste (HCW) management poses significant risks to the environment, human health, and socio-economic sustainability due to the infectious and hazardous nature of HCW. This research aims at rendering a comprehensive landscape of the body of research on HCW management by (i) mapping the scientific development of HCW research, (ii) identifying the prominent HCW research themes and trends, and (iii) providing a research agenda for HCW management towards a circular economy (CE) transition and sustainable environment. The analysis revealed four dominant HCW research themes: (1) HCW minimization, sustainable management, and policy-making; (2) HCW incineration and its associated environmental impacts; (3) hazardous HCW management practices; and (4) HCW handling and occupational safety and training. The results showed that the healthcare industry, despite its potential to contribute to the CE transition, has been overlooked in the CE discourse due to the single-use mindset of the healthcare industry in the wake of the infectious, toxic, and hazardous nature of HCW streams. The findings shed light on the HCW management domain by uncovering the current status of HCW research, highlighting the existing gaps and challenges, and providing potential avenues for further research towards a CE transition in the healthcare industry and HCW management.

Keywords: Waste management; Healthcare waste; Circular economy; Environmental sustainability; Hazardous waste; Medical waste

Abbreviations

Abbreviation	Full term
AHP	Analytical Hierarchy Process
ANP	Analytical Network Process
APCD	Air Pollution Control Device
BMW	Bio-medical Waste
BMWM	Bio-medical Waste Management
COD	Chemical Oxygen Demand

FMEA	Failure Mode and Effects Analysis
HCF	Healthcare Facility
ISM	Interpretive Structural Modeling
KAP	Knowledge, Attitude, and Practice
LCA	Life Cycle Assessment
MCDM	Multi-criteria Decision-making
MW	Medical Waste
MWI	Medical Waste Incinerator
MWM	Medical Waste Management
NHS	National Health Service
PAH	Polycyclic Aromatic Hydrocarbon
PCB	Polychlorinated Biphenyl
PCDD	Polychlorinated Dibenzo-dioxin
PCDD/F	Polychlorinated Dibenzo-furan
PPE	Personal Protective Equipment
PVC	Polyvinyl Chloride
RFID	Radio Frequency Identification
SMW	Solid Medical Waste
SMWM	Solid Medical Waste Management
SWM	Solid Waste Management
SPSS	Statistical Package for the Social Sciences
TCLP	Toxicity Characteristic Leaching Procedure
WAO	Wet Air Oxidation
WM	Waste Management

1. Introduction

As one of the fastest-growing global industries, the booming healthcare industry is increasingly generating waste more than ever by providing a multitude of goods and services to control diseases and treat patients (Kenny and Priyadarshini, 2021). The generated healthcare waste (HCW) can highly affect environmental sustainability (Alharbi et al., 2021) and community health (Dang et al., 2021). Furthermore, with an increase in population index and growth in healthcare facilities (Thakur et al., 2021), the global generation of HCW follows a growth rate of 2–3%. The HCW growth rate is even faster in China, which is expected to reach a volume of 2.496 million tons in 2023 (Li et al., 2021). Therefore, HCW, as a major environmental concern, needs proper management and adopting suitable treatment strategies before final disposal to reduce its harmful impacts (Alam and Mosharraf, 2020). In this vein, safe mechanisms to accurately segregate, collect, transport, treat and dispose of HCW are pivotal for HCW management to ensure environmental protection and socio-economic sustainability. However, properly implementing HCW management policies is facing many challenges, such as lack of budget allocation by the hospital administration, unskilled workers handling the infectious waste, and outdated technologies and methods used to dispose of HCW (Thakur et al., 2021). For instance, according to the assessment provided by the World Health Organization (WHO) in 2015, only 58% of the sampled facilities from 24 countries all around the world had proper systems to deal with the safe disposal of HCW (WHO, 2015a).

A tremendous amount of research on different streams of HCW has been carried out over the last decade. Efforts within the existing literature have been mainly focused on but not limited to perceived risk and associated factors of HCW (Karki et al., 2020), developing indicators for HCW management (Barbosa and Mol, 2018; Ferronato et al., 2020), hazardous medical waste (Komilis et al., 2012; Marinković et al., 2008), HCW incineration (Anastasiadou et al., 2012; Gidarakos et al., 2009), sustainable environmental management of HCW (Alharbi et al., 2021), HCW treatment technologies (H. Li et al., 2020), and more recently, HCW management challenges during the COVID-19 pandemic (de Aguiar Hugo and Lima, 2021). Although delivery of high-quality care is the main priority for the healthcare industry, waste minimization and preparation for reuse, recycling, and recovery programs based on the circular economy (CE) model should be considered to save both environmental and financial resources (Voudrias, 2018). Nevertheless, the literature lacks a comprehensive understanding of how a CE model can take in place to deal with HCW due to its infectious and hazardous nature, which poses a serious threat to the environment and human health. On the other hand, the outbreak of the COVID-19 pandemic has even made the disposing of HCW in a sustainable manner more complicated, with highly infectious waste coming from patients and healthcare workers (Chauhan et al., 2021). Moreover, due to the fragmented literature of HCW research, an inclusive framework of HCW research themes and trends towards a CE transition and sustainable environment is still blurred, calling for more investigation.

The main purpose of the current research is to provide a comprehensive image of the body of research on HCW management taking the CE and environmental sustainability into account. To this end, an analytical method, combining bibliometric, text mining, and qualitative content analyses, is employed to address three research questions (RQs) as follows.

RQ1. How has the research landscape of HCW management developed?

RQ2. What are the prominent research themes and areas of HCW?

RQ3. What are the future research directions for HCW management towards a CE transition and sustainable environment?

The present research is the first broad-based study that employs a mixed-method approach to render a state-of-the-art review of HCW streams considering the CE and environmental sustainability to the best of the authors' knowledge. Thus, our review study broadly contributes to (i) understanding the field of HCW and its main research themes and subject areas towards a cleaner environment, (ii) providing insightful guidelines and policies for practitioners and policy-makers involved within the HCW supply chain to support environmental sustainability and transitioning towards a CE, and (iii) identifying research gaps and offering future avenues for research on sustainable HCW management towards implementing a CE within the healthcare industry.

The remainder of the present paper is organized as follows. Section 2 provides an overview of the current challenges of HCW streams towards a CE transition and sustainable environment. The research design and methodology are presented in section 3. The main findings of the research are analyzed and discussed in section 4. Section 5 shares the implications for research by offering future research directions, followed by section 6 that concludes the remarks and highlights the limitations of the study.

2. Healthcare waste streams: an overview

The concept of HCW refers to any waste generated through the process of delivering healthcare services by healthcare facilities, such as hospitals and clinics, or in any other place by individuals or households. A diversity of classifications exists for HCW, mainly dividing the total stream into hazardous and non-hazardous fractions, representing 75–90% and 10–25% of the total HCW, respectively (WHO, 2014), as illustrated in Figure S1 in Supporting Information. Non-hazardous fraction of HCW, also known as general HCW, is usually similar to municipal solid waste and includes paper, plastic, glass, and food residues and containers, generated mainly from the kitchen, administrative, and housekeeping activities within the healthcare facilities (Oduro-Kwarteng et al., 2021). In contrast with non-hazardous waste that does not result in any particular chemical or physical hazard, the hazardous fraction of the HCW may result in a range of environmental and health risks (Domingo et al., 2020). The hazardous HCW is classified into different categories according to the type, source, and risk factors related to its handling, transport, storage, and final disposal (WHO, 2017). This waste stream includes sharps, infectious waste, obsolete or expired chemical products, pharmaceuticals, anatomical and pathological waste, and radioactive waste (UN, 2011). Notably, the disposal costs of hazardous wastes are ten times more than non-hazardous waste (Amariglio and Depaoli, 2021). Therefore, when reporting HCW generation rates, adequately identifying the types and quantities of HCW produced is significantly crucial in proper and safe HCW management (Minoglou et al., 2017).

The WHO and International Atomic Energy Agency have elaborated some policy documents and guidelines to support countries in implementing better HCW management systems (UN, 2011). Furthermore, many countries have signed and ratified such international conventions as Basel Convention on Hazardous Waste, Stockholm Convention on Persistent Organic Pollutants, and Minamata Convention on Mercury. In addition, most of the developed countries adopted national legislative and administrative regulations to create a sustainable HCW management system (Rizan et al., 2021). Figure 1 summarizes the various levels of HCW governance with a focus on European Union countries. Obviously, in line with the global agreements and conventions set by the WHO and the International Atomic Energy Agency, European Union has also laid several legislations, directives, strategies, and action plans to improve waste management practices in Europe, part of which refers to HCW. These directives and action plans include but are not limited to the Waste Framework Directive (European Council, 2008), European Green Deal (European Commission, 2019), Circular Economy Action Plan (European Commission, 2015), and Directive on single-use plastics (EU, 2019). Furthermore, at the regional level, the European Commission has adopted an Economic and Investment Plan for the Western Balkans (European Commission, 2020a) and the Green Agenda in the Western Balkans (European Commission, 2020b) to support the green recovery of the countries of the region. Furthermore, as a regional cooperation program, the Environmental Partnership Program for Accession was funded by the European Union for a duration of three years (2019–2022) to support the development in environmental governance in the Western Balkans and Turkey (EU, 2020). These initiatives are followed by laws, policies, strategies, action plans, guidelines, and steering committees at the national level in each country and are considered and followed by local communities, including zero-waste NGOs, business sectors, local scientific communities, and other local stakeholders.

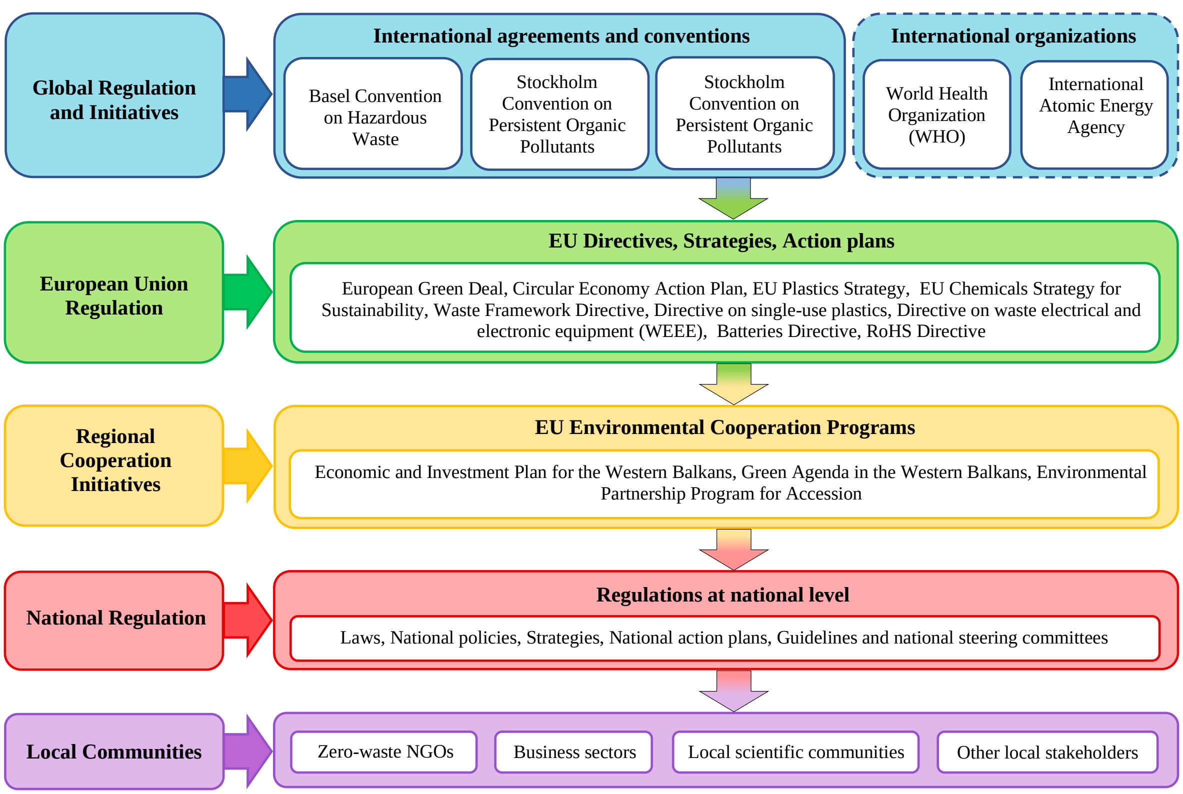

Fig. 1. Various levels of healthcare waste (HCW) governance with a focus on European Union countries.

The status of HCW management systems in most Western Pacific Region and South-East Asia Region countries is presented in the WHO reports (WHO, 2017, 2015b). Despite some good practices outlined in these reports, compliance with HCW management remains a significant challenge in many countries. For instance, some developing countries use open burning and incinerating in single-chamber incinerators as the major means of treating waste (Khan et al., 2019; WHO, 2017). Furthermore, in low- to middle-income countries, HCW is mixed with general domestic waste and disposed of in municipal waste facilities or dumped illegally as the main disposal route in these countries (Baldé et al., 2017; UN, 2011). Consequently, a proper approach for HCW management seems to be vital to be adopted in these countries and continued or improved in countries already considering them.

The CE has been introduced in the literature as a potential approach to reduce the negative environmental impacts of the HCW (Kane et al., 2018; van Straten et al., 2021). The CE approach refers to a regenerative system in which, through slowing, closing, and narrowing supply chain loops, material input, waste, and emissions are minimized (Geissdoerfer et al., 2017). Accordingly, the design framework for the CE is increasingly used in industry to build up product circularity in terms of its multiple-use and recycling (Linder et al., 2020; Shevchenko et al., 2021) and product sustainability in terms of minimizing its negative impact on the environment (Dyllick and Rost, 2017). Some limited CE practices already exist within the HCW management system in various forms and maturity levels (Kane et al., 2018). For instance, the CE approach has been highlighted in the literature as a means of reducing HCW through reusing and recycling durable medical equipment (Ordway et al., 2020), repairing and recycling hospital instruments and surgical stainless steel wastes (van Straten et al., 2021), and replacing disposable products with reusable ones in medical and dental sectors (Antoniadou et al., 2021). Besides, recovering value from disposables, such as using medical needles in concrete production, has also been stressed in the existing studies (Hamada and Ismail, 2021). However, there is a lack of decent academic discussion regarding the application of CE principles and practices to increase resource efficiency in the healthcare industry and reduce the adverse environmental effects of both hazardous and non-hazardous HCW.

3. Research design

The present research followed a mixed-method approach adopted from Ranjbari et al. (2021b) by employing an analytical method to map the scientific literature of HCW, as illustrated in Figure 2. The rationales behind adopting this mixed-method approach are (1) unfolding the theoretical foundations and developments of HCW research by conducting an analysis based on a massive database and (2) taking advantage of the ability of bibliometric and text mining analyses to identify established past evolutions and emerging topical areas (Ertz and Leblanc-Proulx, 2018) within a huge amount of publications in the literature in a reasonable manner. Data collection and the process of analyzing the data are explained in the following sections.

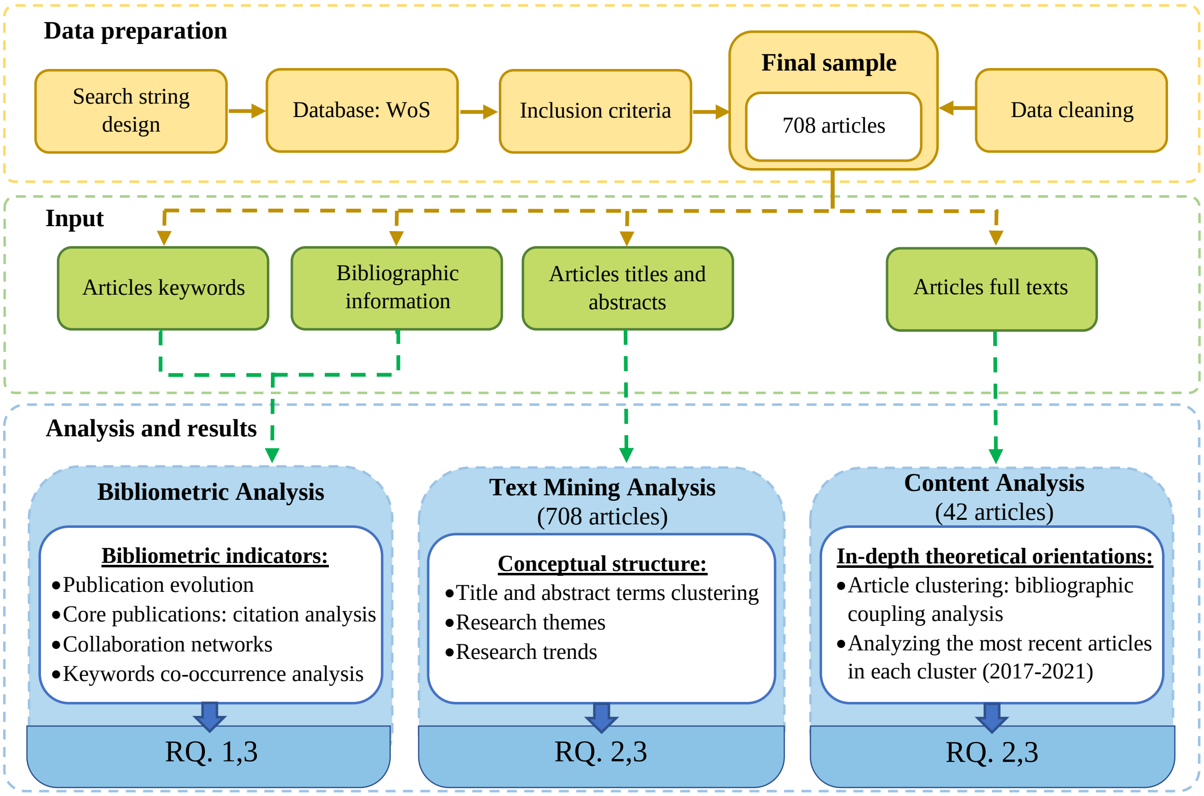

Fig. 2. Research framework adopted for mapping healthcare waste (HCW) management research from 1985 to 2021.

3.1. Data collection and preparation

The Web of Science (WoS) database, as one of the most trusted publisher-independent global citation databases in academia, was selected for collecting data herein. A combination of different keywords directly addressing the scope of our study was extracted from literature and elaborated to design the following search string: "healthcare waste" OR "medical waste" OR "hospital waste" OR "clinical waste" OR "infectious waste" OR "sharps waste" OR "pathological waste" OR "pharmaceutical waste" OR "biomedical waste" (search in the title of articles) AND "environment*" OR "sustainab*" OR "circular economy" OR "circularity" OR "closed loop" OR "reduc*" OR "reus*" OR "recycl*" OR "hazard*" OR "manag*" (search in the title, abstract, author keywords, and keywords plus of articles). Only peer-reviewed journal articles in the English language were considered (i.e., conference proceedings, editorial, reports, book chapters, etc., were excluded) with no time limit. The search process was started in early March 2021 and stopped on June 4, 2021, with a final sample consisting of 708 articles. Table S1 in Supporting Information summarizes the search protocol.

Data cleaning was carried out in a reasonable manner on the final database to prepare the input for the keywords co-occurrence and text mining analyses (Ranjbari et al., 2020). Hence, the singular and plural forms and the full and short (abbreviation) forms of author keywords were unified to avoid separately counting words with the same meanings. Furthermore, while different words with similar meanings, such as "social impact" and "social effect" were unified within author keywords, titles, and abstracts, general words without explicit meaning for the main focus of the current study, such as "article" and "review" were removed from the author keywords to enhance the solidity of the obtained results from the analyses. The unification of writing styles was also done to merge the words and terms with a different spelling but the same meaning, such as "optimisation" and "optimization" or "modelling" and "modeling" within the author keywords, titles, and abstracts of the articles.

3.2. Data analysis

As an effort to map the scientific literature of HCW, the present research employed a mixed analytical method. The applied research method was informed by incorporating a bibliometric analysis, a text mining analysis, and a qualitative content analysis to effectively extract information from a huge database of documents and draw an inclusive snapshot of HCW evolution, characteristics, practices, challenges, major research themes and trends, and future perspectives.

The use of large datasets and keyword-based analyses in reviewing the academic literature has been growing over recent years. Bibliometric analysis is a systemic approach that quantitatively analyzes scientific literature (Zhang et al., 2019) to provide the main research trends of a field of study and measure the research performance of journals, researchers, institutions, countries, and research fields within academia (Li et al., 2018). Scholars have widely used this analysis as a powerful statistical tool to evaluate the scientific progress of various streams of waste management research, such as food waste (Zhang et al., 2018) and e-waste (Gao et al., 2019). The bibliometric analysis herein was conducted using the VOSviewer software (version 1.6.16) (van Eck and Waltman, 2010) to map the HCW literature taking environmental sustainability and the CE into account for the first time. Hence, a comprehensive overview of the bibliometric status of HCW research, including publications trends, core journals and articles, scientific co-authorship networks, bibliographic coupling of documents, and keywords co-occurrence analysis, are presented herein. Moreover, a text mining analysis was conducted on the titles and abstracts of the articles based on a term co-occurrence algorithm to unfold semantic conceptual structures and latent research themes, which best characterize the relevant literature.

Consistent with the research carried out by Jia and Jiang (2018) and Ranjbari et al. (2021b), a qualitative content analysis was also conducted herein as a complementary layer to deepen the provided insights of the study. Accordingly, due to the high number of articles within the dataset, a bibliographic coupling analysis was conducted to cluster the articles with similar characteristics. Consequently, the contents of the most recent articles over the last five years (2017–2021) within each cluster of articles were scrutinized to investigate the theoretical orientations in HCW management.

4. Results and Discussion

The obtained results are presented and discussed in the following three sub-sections. First, the main findings of the bibliometric analysis are presented to reveal the general status of HCW research in section 4.14.1. Second, the identified main HCW research themes are analyzed and discussed through text mining analysis in section 4.2. And finally, the insights provided by the content analysis are discussed in section 4.3.

4.1. Findings of the bibliometric analysis

The bibliometric parameters analyzed in this research, including chronological distribution of publications, analysis of core journals, influential articles, collaboration networks, funding agencies analysis, and keywords co-occurrence analysis, are presented in the following sub-sections.

4.1.1. Chronological distribution of publications

Searching in WoS revealed that a total of 708 articles had been published between 1985 and June 2021 that fits our search string and selection criteria. The first research was conducted by Mailhson (1985) and published in American Journal of Infection Control as a critical review of the draft manual for infectious waste management from the Environmental Protection Agency. According to Figure S2 in Supporting Information, the overall growth of the published peer-reviewed journal articles has increased since 2006, with some minor dints in the number of publications up to now.

4.1.2. Analysis of core journals

With respect to the source journals, the 708 articles of our sample have been published in 314 journals indexed in WoS. Among all the 314 journals, 224 journals only published one article. The top ten most productive journals in terms of the number of publications in the HCW research domain, accounting for 32.2 % of the total published articles in our database (228 out of 708), are presented in the upper part of Figure 3**Error! Reference source not found.**. Based on the results, *Waste Management & Research* is the most productive journal with 81 articles, and therefore, plays a significant role in the HCW research domain. The second and third most productive journals are *Waste Management* and *Fresenius Environmental Bulletin* with 52, and 17 publications, respectively.

The number of articles published by each of the mentioned top ten most productive journals during the recent five years (2017–2021) is shown in Figure S3 in Supporting Information. *Waste Management & Research*, the leading journal in terms of the publications number in the whole dataset, has followed a growing trend within the recent 5-year period and has managed to be the leading journal within this period. Conversely, *Waste Management*, the second most productive journal in our dataset, has not shown a growth rate in terms of productivity during the past five years, despite publishing five articles in 2017–2021. Besides, although *Journal of Hazardous Materials* and *Journal of Hospital Infection* are ranked 7^{th} and 8^{th} productive journals, respectively, they have had no record of publication from 2017 onwards in our database. However, a jump could be observed in terms of the number of publications by *Journal of Cleaner Production* in 2021, and a considerable increase in the number of publications by *Fresenius Environmental Bulleting* in 2019 and 2020.

Figure S4 in Supporting Information shows the publication trend of the journals with at least five articles in the period 2017–2020 in our dataset. Reappearing *Waste Management & Research*, *Waste Management*, *Fresenius Environmental Bulleting*, *Environmental Science and Pollution Research*, *Journal of Material Cycles and Waste Management*, and *Journal of Cleaner Production* in Figure S4 in Supporting Information shows that not only these journals are among the top ten most productive journals in this field of study, but also they could retain their success in being among the most productive journals over the past five years. However, *Journal of the Air & Waste Management Association*, *Journal of Hazardous Materials*, *Journal of Hospital Infection*, and *Americal Journal of Infection Control* have not appeared in Figure S4 in Supporting Information. *Sustainability*, *Journal of Environmental and Public Health*, and *Science of the Total Environment* are the recent journals in the list of most productive journals in the past five years.

On the other hand, the lower part of Figure 3 **Error! Reference source not found.**shows the top ten most influential journals regarding the number of citations they have gained until June 2021 based on the WoS database. *With a total of 2302 citations, Waste Management* is the most-cited journal, attracting the great attention of scholars in the HCW research area. The following influential journals are *Waste Management & Research*, *Journal of Environmental Management*, and *Journal of Hazardous Materials* with 994, 403, and 377 total citations, respectively.

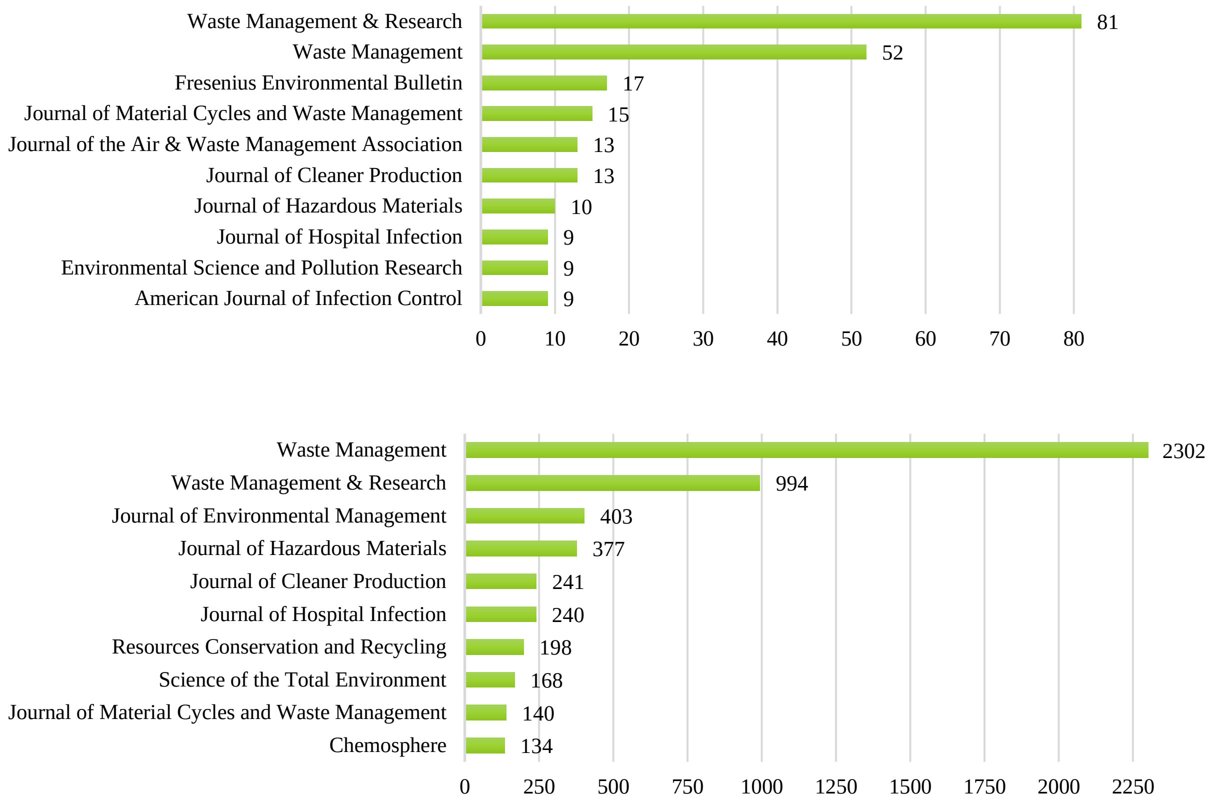

Fig. 3. Top ten most productive journals in terms of the number of publications (upper figure) and top ten most influential journals regarding the number of citations (lower figure).

4.1.3. Influential articles

The number of citations to scientific articles could be used to measure their influence on the related research area (Merigó et al., 2015). Table S2 in Supporting Information lists the top ten most influential articles within the HCW research domain in our dataset. As shown in Table S2, the most influential article with 135 citations is an inclusive review paper conducted by Windfeld and Brooks (2015) that has provided an overview of medical waste management practices focusing on the common sources, governing legislation, and handling and disposal methods. Consistent with the previous article, Jang et al. (2006) carried out the second highly cited article with 130 citations to present an image of the current medical waste management practices considering generation, composition, segregation, transportation, and disposal of HCW in Korea. A system dynamics modeling research developed by Chaerul et al. (2008) is ranked the third among influential articles, which has determined the interaction among factors in the HCW system, highlighting the importance of proper waste segregation and infectious waste treatment prior to disposal in developing countries. Suitable toxicity evaluation of HCW (Tsakona et al., 2007) and the issues regarding safe management of hazardous medical waste generated by hospitals (Marinković et al., 2008) are also included in the most influential articles. Moreover, among the top ten most influential articles, Iranian authors with two case studies from Iranian hospitals were ranked fourth (Askarian et al., 2004) and tenth (Taghipour and Mosaferi, 2009), focusing on the characterization of HCW. The Journal *Waste Management* with six influential articles out of ten has a considerable contribution to the HCW research.

4.1.4. Collaboration network analysis and funding agencies

A total of 90 countries contributed to the HCW research in our dataset. Among all these countries, there were 66 countries connected to others, constructing a collaboration network, as illustrated in Figure S5 in Supporting Information. The size of the circles and the thickness of the links between each pair of circles in the networks correspond to the number of articles of a country or institution and the strength of collaboration between the two entities, respectively.

As shown in Figure S5 in Supporting Information, India with 108 HCW-related articles is placed in the topmost position of productive countries. India is closely followed by China as the second most productive country with 107 articles. In this vein, the USA, Iran, England, and Turkey are the following productive countries with 59, 50, 48, and 35 HCW-related research, respectively. Moreover, with respect to the number of collaborations with other countries, China with 44 international collaborations (mostly with Pakistan, the USA, England, and Japan) is ranked first. England with 33 and India with 26 international links come next as the second and third most collaborative countries. On the contrary, Taiwan with one and Greece and Brazil with three links have the lowest level of collaboration among the top ten countries in the list.

The results show that developing countries have had a considerable role in constructing the body of knowledge in the HCW research, since six out of the top ten productive countries are from these countries, including India, China, Iran, Turkey, Brazil, Pakistan, and Taiwan. Nevertheless, HCW management in developing countries has not received sufficient attention (Abd El-Salam, 2010), and many of these countries still suffer from inappropriate medical wastes disposal and treatment methods. This issue may be due to the lack of required infrastructure, technological advancements, budget, regulation, and legislative enforcement. However, the gap between high scientific HCW-related production in academia and low adaptation of suitable HCW strategies in practice to take a sound HCW management system in place could be an issue of debate for more investigation within the context of developing countries.

In terms of institutional contribution, a total of 929 institutions in our database have conducted research in the HCW context. To illustrate the collaboration network among institutions, the largest set of connected institutions consisting of 123 unique institutions were plotted, as shown in Figure S6 in Supporting Information. Chinese Academy of Sciences with 16 articles and Zhejiang University with 14 articles both from China, and Tehran University of Medical Sciences with 13 articles from Iran are the most productive institutions in HCW research. Moreover, the top three actively collaborating organizations in the studied database are Tehran University of Medical Sciences, Chinese Academy of Sciences, and University of Northampton with 23, 22, and 19 collaboration links, respectively. Iranian institutions appeared as the leading organizations in shaping the literature of HCW-related research since four institutions out of the top ten contributing institutions are from Iran. Tehran University of Medical Sciences is notably highlighted as the first institution in terms of the number of collaboration links with other institutions and the third institution in terms of the number of contributions.

Only 230 out of the 708 articles in our database received funding supports. However, many of these research projects were funded by more than one source. More specifically, 311 funding agencies were involved in supporting these 230 research works. Figure S7 in Supporting Information presents the funding agencies supporting more than three research pieces in our database. Notably, 10 out of these 11 funding agencies are from China, which significantly highlights the important role of China in supporting research in the field of HCW management. National Natural Science Foundation of China, with 49 funding records, is the leading funding agency in this field, followed by the National Basic Research Program of China with 11 records, as the second most supporting program. Fundamental Research Funds for the Central Universities and the National Key Research and Development Program of China, each with 9 records of financial support, are ranked third in terms of funding the research projects in this field of study. European Commission, which is the only non-Chinese funding agency on the list of most supporting funding agencies, comes next with 8 records of funding. Remarkably, although India has contributed more than China in terms of the number of publications in this field of research, no Indian program appeared on the list of top funding agencies. Besides, while the USA, Iran, England, Turkey, Brazil, Pakistan, Greece, and Taiwan, are ranked the top ten productive countries, there is no funding agency from these countries within the top contributing funding agencies.

4.1.5. Keywords co-occurrence analysis

The rationale behind conducting keywords co-occurrence analysis is that authors' keywords can effectively convey the main idea and border of the scope of articles and their content (Comerio and Strozzi, 2019). The keywords co-occurrence analysis, as a tool to identify research hotspots and focal nodes within the context of a particular subject (Gao et al., 2020), has been widely used in recent bibliometric studies. Co-occurrence of keywords refers to the appearance of two keywords together in a single publication, indicating that a relationship link exists between the two concepts (Baker et al., 2020).

After data cleaning and unifying keywords as explained in the methodology section, the top 20 most frequent author keywords used in the HCW research (among the 1467 keywords in our database) are presented in Table S3 in Supporting Information. On this basis, medical waste, waste management, HCW, biomedical waste, and incineration are the top five most frequent keywords with 156, 84, 62, 59, and 43 frequency of occurrence, respectively. The focus of these keywords is mainly on managing the HCW systems and proper disposal/treatment methods with an emphasis on the incineration of the hospital and clinical wastes. Hospital waste, hospital, HCW management, infectious waste, heavy metal, medical waste management, environment, hazardous waste, knowledge, management, incinerator, segregation, COVID-19, biomedical waste management, and clinical waste were the next most frequent keywords in the HCW literature. While "total links" denotes the number of keywords with which each keyword has a connection link, "total links strength" shows the number of connection links each keyword has with other keywords. Therefore, medical waste, waste management, and HCW have both the highest total links and total links strength scores in our database, highlighting the significant role of these keywords within the body of knowledge in HCW research.

The co-occurrence network of the keywords within the HCW research is visualized in Figure 4. Due to the large number of keywords, only keywords with a minimum occurrence of two have been plotted (273 keywords out of 1467) to increase the visibility of the network map. As shown in Figure 4, more occurrences of the keywords are reflected through larger circles, and thicker links between them show a higher number of co-occurrence of a pair of keywords. Besides, the colors of keywords' circles moving from blue (older) to red (more recent) are based on the average publication year in which a keyword occurs.

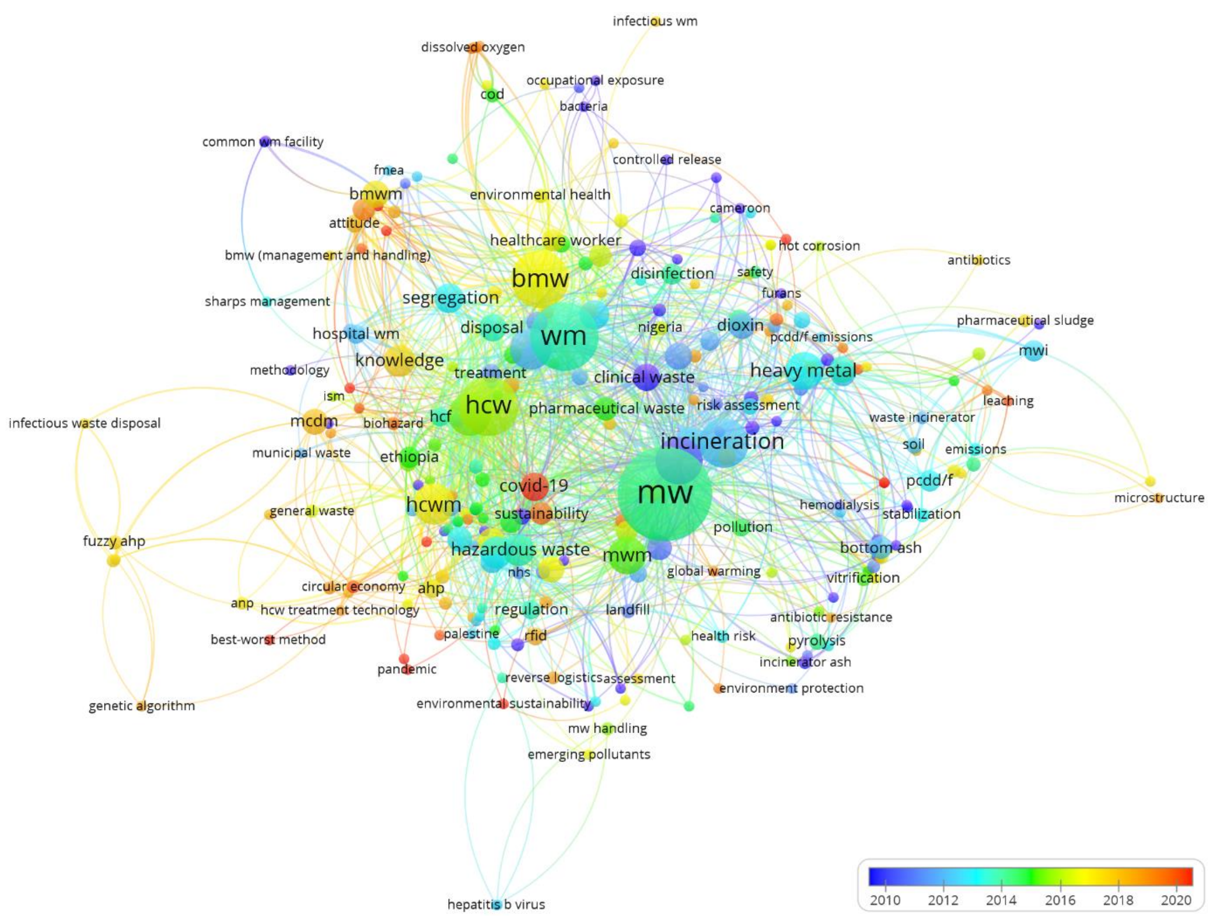

Fig. 4. Co-occurrence network of the keywords within the healthcare waste (HCW) research.

Legend: AHP: Analytical hierarchy process; **ANP**: Analytical network process; **APCD**: Air pollution control device; **BMW**: Biomedical waste; **BMWM**: Biomedical waste management; **COD**: Chemical oxygen demand; **FMEA**: Failure mode and effects analysis; **HCF**: Healthcare facility; **ISM**: Interpretive structural modeling; **KAP**: Knowledge, attitude, and practice; **LCA**: Life cycle assessment; **MCDM**: Multi-criteria decision-making; **MW**: Medical waste; **MWI**: Medical waste incinerator; **MWM**: Medical waste management; **NHS**: National health service; **PAH**: Polycyclic aromatic hydrocarbon; **PCB**: Polychlorinated biphenyl; **PCDD**: Polychlorinated dibenzo-dioxin; **PCDD/F**: Polychlorinated dibenzo-furan; **PPE**: Personal protective equipment; **PVC**: Polyvinyl chloride; **RFID**: Radio frequency identification; **SMW**: Solid medical waste; **SMWM**: Solid medical waste management; **SWM**: Solid waste management; **TCLP**: Toxicity characteristic leaching procedure; **WAO**: Wet air oxidation; **WM**: Waste management.

The top 20 most frequent pairs of keywords that most co-occurred in HCW research are listed in Table S4 in Supporting Information. The link between the medical waste and waste management nodes in the co-occurrence network is the most prominent co-occurrence link with a strength score of 25, indicating that HCW research has primarily centered on waste management practices. Moreover, waste management has appeared six times among the nodes contributing to the top 20 most frequent co-occurrence links. This shows an overwhelming interest in academia in the issue of developing effective managerial frameworks for HCW towards a sustainable environment. The second most co-occurred nodes are incineration and medical waste with 18 co-occurrences in the database, highlighting the importance of safe and proper disposal of medical waste to mitigate the adverse effects of incineration on the environment and public health. Notably, mitigating the environmental- and health-related consequences of the incineration process is a matter of the utmost importance for HCW management practitioners and policy-makers. Adopting proper segregation and collection methods for biomedical waste, particularly in dealing with hazardous waste, has also appeared in the most salient nodes and links of the co-occurrence network of HCW-related keywords.

4.2. Text mining analysis: identifying salient research themes

Having conducted a text mining analysis on the concatenation of the titles and abstracts of all 708 articles, a total of 14,578 terms was detected. According to the relatedness of the terms based on a co-occurrence links algorithm, the extracted terms were clustered. A threshold of at least five occurrences of terms was applied for more visibility of the identified themes and their associated terms. As a result, four main HCW research themes were discovered, including: (i) HCW minimization, sustainable management, and policy-making, (ii) HCW incineration and its associated environmental impacts, (iii) hazardous HCW management practices, and (iv) HCW handling, and occupational safety and training. Figure 5 visualizes the conceptual structure of HCW research and its four main research themes in the literature. Moreover, a sample of the most relevant terms included in each research theme and also some recent exemplary references are provided in Table 1.

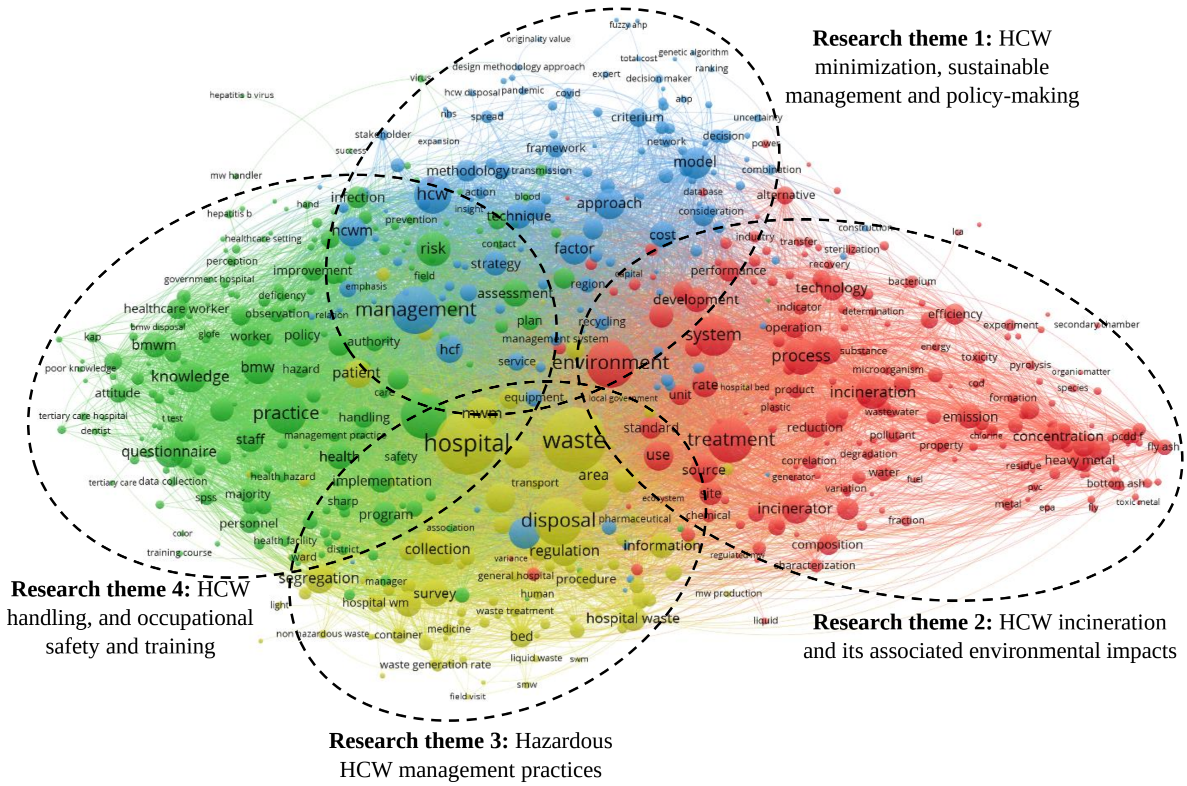

Fig. 5. Visualization of the main identified research themes of healthcare waste (HCW) research in the literature.

Table 1. Main terms included in the identified healthcare waste (HCW) research themes in the literature.

Research theme	Leading terms	Exemplary articles
1. HCW minimization, sustainable management, and policy-making	Analytical hierarchy process, Complexity, COVID-19, Crisis, HCW, HCW disposal, HCW generation, HCW management, Infectious HCW, Infectious waste disposal, Location, Management system, Minimization, Model, Optimization, Planning, Potential environmental hazard, Potential risk, Prediction, Radio frequency identification technology, Sustainable management, Treatment facility, Treatment technology, Uncertainty, Waste minimization	Tirkolaee et al. (2021), Kargar et al. (2020), Wichapa and Khokhajaikiat (2017), Valizadeh and Mozafari (2021), Gao et al. (2021), Geetha et al. (2019), Wichapa and Khokhajaikiat (2018)
2. HCW incineration and its associated	Incineration, Medical waste incinerator, Heavy metal, Fly ash, Dioxin, Polychlorinated dibenzo-furan (PCDD/F), Bottom ash, Contamination, Medical waste	Li et al. (2020), Kaur et al. (2019), Kaur et al. (2021), Ma et al. (2020),

	environmental impacts	treatment, Polychlorinated dibenzo-dioxin (PCDD), Toxicity, Combustion, Pathogen, Sterilization, Landfilling, Flue gas, Polycyclic aromatic hydrocarbon, Leachability, Microorganism, Pyrolysis, Furan, Polyvinylchloride, Chemical oxygen demand, Medical waste incinerator fly ash, Polychlorinated biphenyl, Toxicity characteristic leaching procedure, Incineration technology, Life cycle assessment, Staphylococcus aureus, Air pollution control device, Chlorine, Environmental contamination, Antibiotic resistance, Organic matter, Toxic metal	Zhang et al. (2020), Su et al. (2021), Zhao et al. (2009), Mahdi and Gomes (2019)
3.	Hazardous HCW management practices	Infectious waste, Segregation, Hazardous waste, Pharmaceutical waste, Medicine, Hazardous waste management, Sharps waste, Liquid waste, Pharmaceutical waste management, Medical waste control regulation, Scavenger, Hazardous nature, Unused medicine	Bungau et al. (2018), Hassan et al. (2018), Al-Khatib et al. (2020), Mohamed et al. (2009), Manojlović et al. (2015), Marinković et al. (2008)
4.	HCW handling and occupational safety and training	Biomedical waste, Biomedical waste management, Infection, Sharp, Health hazard, Needle, Personal protective equipment, "Knowledge, Attitude, and Practice", Medical waste management practice, Syringe, Biomedical waste management practice, Training program, Blood, Healthcare staff, Infectious waste management, Injection, Waste management policy, Body fluid, Medical waste handler, Biomedical waste disposal, Biomedical waste management rule, Clinical waste management, Immunization, Infection control, Infectious agent, Infectious disease, Needle-stick injury	Behnam et al. (2020), Abdo et al. (2019), Robat et al. (2021), Gonibeedu et al. (2021), Akkajit et al. (2020)

One of the four identified dominant HCW research themes is "modeling approaches towards HCW minimization, sustainable management, and policy-making". The studies corresponding to this research theme have been mainly focused on the optimization issue for increasing the performance of HCW management systems, such as routing optimization for urban medical waste recycling networks (Gao et al., 2021) and infectious waste disposal methods (Wichapa and Khokhajaikiat, 2017). On the other hand, multi-criteria decision-making methods have been widely employed within the first research theme for different purposes, such as developing assessment models for HCW disposal (Geetha et al., 2019) and choosing proper locations for infectious waste disposal as a critical issue in hazardous waste management to decrease the risk imposed on the environment (Wichapa and Khokhajaikiat, 2018). Moreover, optimization methods have been found useful in HCW management during the COVID-19 pandemic through (1) developing cooperative models for the collection of infectious waste generated due to the pandemic (Valizadeh and Mozafari, 2021), (2) sustainable multi-trip location-routing problems for medical waste management during COVID-19 (Tirkolaee et al., 2021), and (3) reverse logistics network design for medical waste management after COVID-19 (Kargar et al., 2020).

The second main research theme within the HCW-related academic literature is "incineration of HCW and its associated environmental impacts". Incineration is the most frequently used treatment technology for HCW due to its capability to sterilize the pathological and anatomic waste, reduce the volume and mass, and recover energy (Zhao et al., 2009). However, the incineration process produces solid residues, such as bottom and fly ash, and off-gas cleaning residues containing heavy metals and inorganic salts (Anastasiadou et al., 2012). Moreover, waste incineration due to incomplete combustion may generate by-products with polycyclic aromatic hydrocarbons, which are highly carcinogenic, teratogenic, mutagenic, and genotoxic (Mahdi and Gomes, 2019). Besides, the improper disposal of bottom ash remaining from the infectious HCW incineration has caused significant damages to the environment and public health due to its high contamination effect on the soil and surface and underground waters (Gidarakos et al., 2009). The articles within this research theme have been mainly focused on (1) the influence of incinerated biomedical waste ash, as a fine aggregate replacement, on the properties of concrete (Kaur et al., 2019), (2) developing effective circulating systems for removing hazardous heavy metals in medical waste incineration fly ash (Y.-M. Li et al., 2020), (3) removal of alkalinity and metal toxicity from incinerated biomedical waste ash (Kaur et al., 2021), (4) the application of clean and safe technologies, such as pyrolysis technology (Su et al., 2021), and microwave disinfection in the HCW treatment (Mahdi and Gomes, 2019), and (5) the quantities and characteristics of pollutants emitted during the incineration of medical waste (Ma et al., 2020; Zhang et al., 2020).

Hazardous HCW, as an increasing environmental concern, has shaped a major research theme in HCW research due to its adverse effects on environmental sustainability and human well-being. The main focus of the research in the theme "hazardous HCW management practices" has been on the adequate, proper, and safe identification, quantification, segregation, handling, treatment, and disposal of hazardous HCW, which poses a significant risk to the environment and public health. Hence, scholars have highlighted several issues in dealing with hazardous HCW, such as (1) barriers to taking a proper HCW management in place, including limited documentation regarding generation, handling, and disposal of waste, and failure of planning and training, in particular in developing countries (Hassan et al., 2018; Mohamed et al., 2009), (2) the lack of well-established waste segregation and handling in many hospitals and medical center, indicating the need for activation and enforcement of medical waste laws (Al-Khatib et al., 2020), (3) the role of pharmaceutical waste management in collecting and disposing the medicinal waste of the population (Bungau et al., 2018) and making the public aware of the significance of proper disposal of medications (Manojlović et al., 2015), (4) evaluation of hazardous medical waste generation from different categories of healthcare facilities (Komilis et al., 2012, 2011), and (5) developing integrated frameworks for medical waste management (Marinković et al., 2008).

The last identified HCW research theme is "HCW handling and occupational safety and training", which refers to awareness and adequate knowledge about safe and proper handling and disposal of infectious and hazardous HCW. The sufficient knowledge and practice of healthcare workers to sustainably deal with HCW and its potential risks are indispensable to perform any effective HCW management system (Akkajit et al., 2020). The effectiveness of educational intervention programs based on the knowledge, attitude, and practices (KAP) framework on hospital waste management (Abdo et al., 2019) and assessing the impact of educational training on the behavioral intention for HCW management (Robat et al., 2021) have mainly constructed the body of knowledge of this research theme. Moreover, developing a KAP model for implementing biomedical waste management practices in primary healthcare facilities (Gonibeedu et al., 2021) and for reflecting the inadequacies in existing HCW management practices (Behnam et al., 2020) has been widely considered.

The evolution of the selected main subject areas and research topics within the identified HCW research themes over the recent years is mapped in Figure 6, considering their average publication year. Average publication year calculated based on a binary counting of the terms refers to the average publication year of all the documents that contain a specific term in their titles or abstracts. Therefore, more than one occurrence of a term in an article's title and abstract does not result in a higher weight for the article in the average calculation. Considering the growth of the number of articles on HCW as previously illustrated in Figure S2 in Supporting Information, since the number of articles has notably increased after 2006, the average publication year of the main terms in this field usually appears after 2006. As illustrated in the timeline in Figure 6, research topics such as life cycle assessment, needle-stick injury, human health risk, social responsibility, objective function, KAP, radio frequency identification technology, and COVID-19 have been attracting attention very recently, since their average publication year is between 2018 and 2021. Based on the results, COVID-19 and pandemic have been appeared as the most recent research topics with an average publication year of 2020.647 and 2020.7, respectively. This result is due to the recentness of COVID-19 and the surge of research to respond to the urgent call for action against the pandemic (Ranjbari et al., 2021c, 2021a). Subject areas focusing on unused medicine, biomedical waste management, sharps waste, personal protective equipment, healthcare disposal, pharmaceutical waste, environmental hazards, medical waste incinerator fly ash, treatment technology, infectious HCW, sanitary landfill, and toxicity have been located in the average publication year period of 2013 to 2017. Moreover, incineration, polycyclic aromatic hydrocarbon, infectious agent, landfilling, waste management policy, body fluid, bottom ash, pyrolysis, liquid waste, and combustion have been less attracting attention during the recent years with an average publication year before 2013.

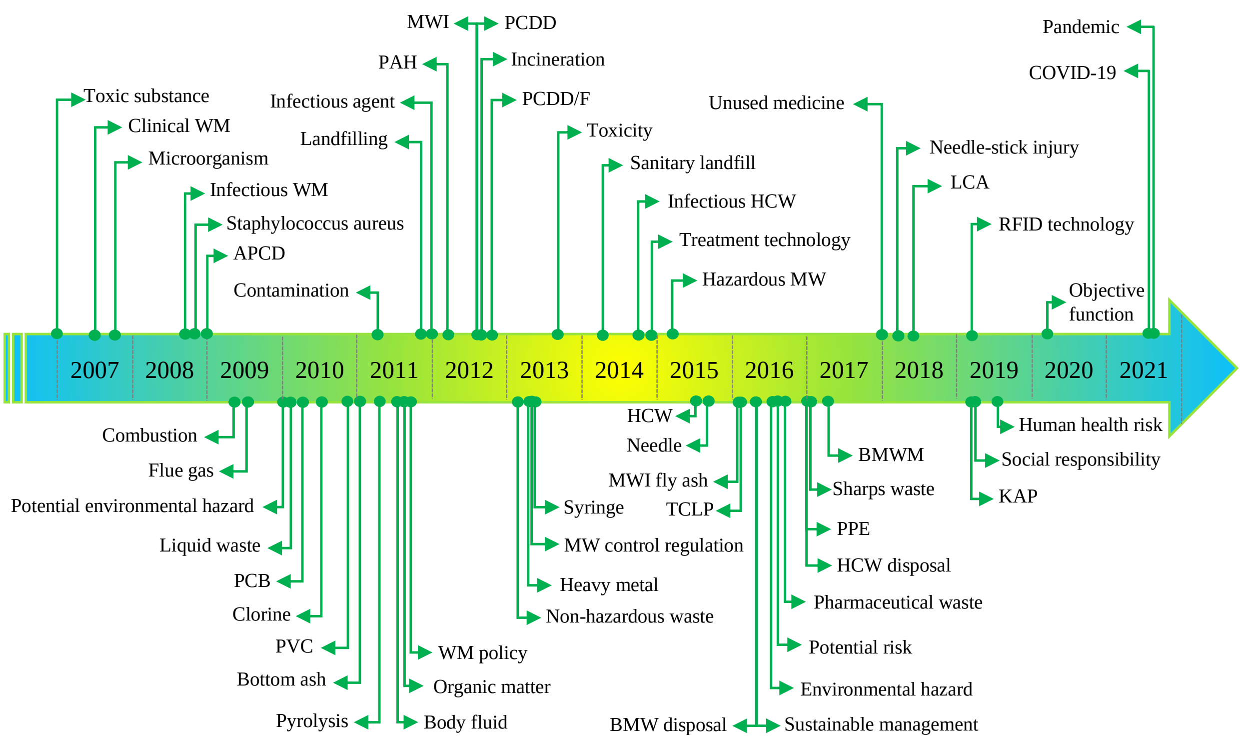

Fig. 6. Timeline of dominant healthcare waste (HCW)-related subject areas of research.

Abbreviations: **APCD**: Air pollution control device; **BMW**: Biomedical waste; **BMWM**: Biomedical waste management; **KAP**: Knowledge, attitude, and practice; **LCA**: Life cycle assessment; **MW**: Medical waste; **MWI**: Medical waste incinerator; **PAH**: Polycyclic aromatic hydrocarbon; **PCB**: Polychlorinated biphenyl; **PCDD**: Polychlorinated dibenzo-dioxin; **PCDD/F**: Polychlorinated dibenzo-furan; **PPE**: Personal protective equipment; **PVC**: Polyvinyl chloride; **RFID**: Radio frequency identification; **TCLP**: Toxicity characteristic leaching procedure; **WM**: Waste management.

4.3. Content analysis

In order to deepen the analysis on the database and unfold theoretical orientations, a content analysis was carried out herein. To overcome the obstacle of a large number of articles (708 articles) for reasonably conducting a sound content analysis, articles were grouped by employing a bibliographic coupling as an article clustering technique. Accordingly, bibliographic coupling analysis based on the number of references commonly cited by the articles revealed five main clusters of HCW-related articles as presented in Table 2. Therefore, the most recent articles of each cluster within the period of 2017 to 2021 were collected to conduct the content analysis for more investigation. As a result, having checked the relevancy of the selected papers to the main focus of the present research, a total of 42 recent articles were chosen as the final sample for the content analysis.

Table 2. Selected most recent research within main clusters of healthcare waste (HCW)-related articles from 2017 to 2021.

Cluster 1: The application of modeling methods for effective HCW management systems	**Cluster 2:** HCW management practices	**Cluster 3:** HCW treatment technologies and methods	**Cluster 4:** Pharmaceutical waste	**Cluster 5:** knowledge, attitude, and practice of HCW management
Liu et al. (2020) Homayouni and Pishvaee (2020) Gao et al. (2021) Yao et al. (2020) Torkayesh et al. (2021) Nikzamir et al. (2020) Yu et al. (2020) Hinduja and Pandey (2018) Narayanamoorthy et al. (2020) H. Li et al. (2020)	Çetinkaya et al. (2020) Ali et al. (2017) Hasan and Rahman (2018) Gunawardana (2018) Yousefi and Avak Rostami (2017) Santos et al. (2019) Mmereki et al. (2017) Wilujeng (2019) Eslami et al. (2017) Khan et al. (2019) Barbosa and Mol (2018)	Liu et al. (2019) Ethica et al. (2018) Trebooniti (2021) Zhang et al. (2020) Li et al. (2017) Ma et al. (2020) Qin et al. (2018) Y.-M. Li et al. (2020) Ababneh et al. (2020) Shen et al. (2019) Samad et al. (2019) Pant (2018)	Chung and Brooks (2019) Ariffin and Zakili (2019) Mitkidis and Mitkidis (2020) Sarkar et al. (2019)	Gonibeedu et al. (2021) Parida et al. (2019) Singh et al. (2018) Woromogo et al. (2020) Mannocci et al. (2020)

4.3.1. Cluster 1: the application of modeling methods for effective HCW management systems

Modeling approaches have been widely used in developing HCW management systems to conceptualize, design, and optimize different HCW activities and practices, such as designing collection and disposal networks, transportation routes optimization, selecting the optimal treatment technologies and locations. Due to the infectious nature of a portion of HCW, effective planning is required in hospital waste transportation. Liu et al. (2020) developed a location optimization model for urban HCW storage sites based on the immune algorithm to increase the efficiency of HCW transport from hospitals to disposal stations. Homayouni and Pishvaee (2020) presented a multi-objective robust optimization model to design a collection and disposal network of hazardous HCW to minimize the transportation and operations risks and costs. Gao et al. (2021) extended an integrated optimization model of urban HCW recycling network considering differentiated waste collection strategies with time windows. Establishing proper HCW disposal centers is crucial to reduce the environmental and public risk of HCW pollution. Yao et al. (2020) proposed a soft-path solution to minimize risks and mitigate the associated costs by optimizing the HCW disposal centers' location-allocation problem. Torkayesh et al. (2021) proposed a decision-making model for HCW landfill location selection with a sustainable development perspective to identify the most convenient locations for landfilling. A bi-objective mixed-integer linear programming model was provided by Nikzamir et al. (2020) to design a logistic network of infectious and non-infectious wastes to minimize the network costs and the risk of exposure to contamination. Besides, a multi-objective mixed-integer program for reverse logistics network design for effective management of HCW in epidemic outbreaks such as COVID-19 was proposed by Yu et al. (2020) to identify the best locations for temporary facilities.

Selection of the optimal treatment technology for medical waste is a complex multi-criteria decision-making problem due to the conflicting and intertwined quantitative and qualitative evaluative criteria (Hinduja and Pandey, 2018). Hence, an integrated decision support framework was developed by Hinduja and Pandey (2018) to assess HCW treatment alternatives and prioritize and select the optimal treatment technology among incineration, autoclaving, microwave disinfection, chemical disinfection, reverse polymerization, and pyrolysis. In line with the research conducted by Hinduja and Pandey (2018), Narayanamoorthy et al. (2020) developed a multi-objective optimization model and showed that autoclaving is the best alternative for biomedical waste disposal treatment methods. On the other hand, H. Li et al. (2020) proposed a multi-criteria decision-making method for evaluating HCW treatment technologies in the emerging economies and indicated that steam sterilization is the best HCW treatment technology among microwave, incineration, and landfilling.

4.3.2. Cluster 2: HCW management practices

Mismanagement of HCW owing to its potential hazard can significantly pose environmental and occupational health risks to the global community. However, implementing effective HCW management practices is not straightforward due to the complexity of its health and environmental effects, economic aspects, and social impacts (Çetinkaya et al., 2020). For instance, Ali et al. (2017) highlighted the main challenges faced by hospitals in developing countries, including (1) suffering from inadequate waste segregation, collection, storage, transportation, and disposal practices, (2) HCW management regulations and legislations lagging behind (which varies from one hospital to another), and (3) the absence of decent training programs for hospital staff. In a survey in Bangladesh, Hasan and Rahman (2018) stated that 56% of hospital workers do not receive any form of training to deal with hazardous waste, and 54% of them do not use any safety equipment or clothing. Besides, a suitable approach to select an effective HCW treatment technology, particularly for treating hazardous waste, is still challenging for municipal authorities (Hasan and Rahman, 2018). Gunawardana (2018), in an empirical analysis of 156 healthcare service providers in Sri Lanka, outlined an urgent need for training the top managers involved in the healthcare industry to create a positive attitude towards adopting new HCW treatment technologies and trends.

Proper actions regarding HCW identification, prediction, segregation, collection, transportation, and disposal in hospitals could control putting the worker's safety at risk. The importance of timely and precisely determining the quantity and quality of infectious HCW was highlighted by Yousefi and Avak Rostami (2017) in effective HCW management systems. Moreover, sustainable HCW management could be implemented only if an adequate waste generation prediction is made; otherwise, investment in this sector would be inefficient (Çetinkaya et al., 2020). In this context, Santos et al. (2019), in a study to evaluate the HCW management in a Brazilian context, showed that more than 55.6% of the generated HCW is general waste, followed by infectious, sharps, and chemicals wastes, with the shares of 39.1%, 2.9%, and 2.4%, respectively. Mmereki et al. (2017) showed that current HCW collection and storage facilities in Botswana in Africa do not operate efficiently, and more focus should be on the segregation of infectious and non-infectious from general waste, pollution prevention, and recovery of valuable materials from healthcare facilities. In another study conducted in 17 representative clinics in Indonesia, Wilujeng (2019) denoted that segregation, collection, and storage of the waste generated by clinics, comprising of 21% sharps, 42% infectious, and 37% general waste, did not comply with the government regulatory standard. Eslami et al. (2017) reported that 14.8% of private hospitals and 24.29% of government hospitals in Iran lack any treatment devices, and hazardous HCW is disposed of without any treatment, showing poor hazardous treatment services. Khan et al. (2019) highlighted the need for replacing outdated incineration plants with autoclaving, steam sterilization, and new practices of pyrolysis to avoid the emission of toxic gases in the Asian developing countries, which lack proper waste segregation, collection, storage, transportation, and disposal. Developing HCW indicators to continuously monitor, handle, and manage HCW generation and its associated risks significantly improves HCW risk management (Barbosa and Mol, 2018) and HCW operation systems from identification at the beginning to the disposal at the end.

4.3.3. Cluster 3: HCW treatment technologies and methods

Implementing effective HCW management practices to a large extent is determined by the treatment technology applied. The application of an HCW technology, which is simultaneously inexpensive (Liu et al., 2019) and environmentally friendly (Ethica et al., 2018), has been a subject of research interest over recent years. According to the study conducted by Jang et al. (2006), HCW treatment technologies such as steam sterilization, chemical disinfection, microwave sanitation, recycling, reverse polymerization, dry heat disinfection, autoclaving, and incineration are considered as alternatives. Some studies highlight that due to the advantages of the incineration method, for instance, destruction of bacteria or viruses, reduction of the waste volume, and the potential for energy reuse, many countries incinerate HCW (Trebooniti, 2021; Zhang et al., 2020). Moreover, incineration is used to dispose of 59–60% of the general HCW worldwide (Li et al., 2017; Zhang et al., 2020). However, the medical waste incinerator is considered a key source of hypertoxic PCDDs and PCDD/Fs emission and heavy metals according to Stockholm Convention.

Therefore, various technologies to remove or reduce these chemicals from bottom ash and fly ash are actively being developed.

To avoid secondary pollution, the academic discussion is still ongoing with a focus on the emission characteristics of PCDD/Fs and heavy metals resulting from the incineration (Ma et al., 2020; Zhang et al., 2020), technologies for the reduction of the emission (Li et al., 2017; Qin et al., 2018), and techniques to remove (Y.-M. Li et al., 2020) or reduce the concentration of heavy metals from the medical waste fly ash (Ababneh et al., 2020; Shen et al., 2019) or detoxify the fly ash (Liu et al., 2019). In particular, various treatment techniques for medical waste fly ash and their merits, demerits, applicability, and limitations have been reviewed by Liu et al. (2018). An effective circulating system based on using EDTA disodium (Na2EDTA) was developed by Y.-M. Li et al. (2020) to remove Cu, Pb, Zn, Cd, and Ni from medical waste fly ash. Shen et al. (2019) proposed a technology to reduce dioxin formation during the incineration process based on using activated carbon, which adsorbs dioxin and pelletizes it with adhesive material. The treatment technology for medical waste incinerator fly ash, which is considered hazardous, to simultaneously detoxify both PCDD/Fs and heavy metals through a successive flotation process was proposed by Liu et al. (2019). Exploring the possibilities of medical waste fly ash recycling in mortar mixtures, Ababneh et al. (2020) proposed using ethylene diaminetetra acetic acid disodium as a chelating agent allowing the reduction of the heavy metals concentration in medical waste fly ash. In addition, the study by Anastasiadou et al. (2012) demonstrated the feasibility of using fly and bottom ash in cement matrices to dispose of them safely in non-hazardous landfills or even to reuse these materials in the construction industry. Another line of studies in academia considered hospital wastewater and focused on the pollution of the groundwater near the biomedical waste treatment facilities (Samad et al., 2019), migration of heavy metals from the biomedical waste autoclave to groundwater (Pant, 2018), and hospital wastewater treatment using hydrolytic bacteria (Ethica et al., 2018).

Even though recycling is an effective way to reduce the amount of HCW, there is a lack of academic debate on the segregation techniques to reduce regulated medical waste at the source of such waste generation. For example, Shinn et al. (2017) showed that almost 33% of all regulated medical waste in Korean hospitals comes from operating rooms. According to their research, while regulated medical waste notably consists of disposable packaging and wrapping materials for sterilization of surgical instruments, the non-regulated medical waste includes recyclable materials, such as plastics, cardboards, papers, and different wrapping materials. Therefore, the reduction in HCW generation could be achieved through the systematic segregation of hospital operating room wastes. Furthermore, researching the hospital recycling issue, McGain et al. (2015) argued that due to the lack of appropriate hospital-related recycling companies, there is a necessity to encourage local manufacturers to reduce the amount of packaging used or to change the materials used, which is still challenging.

4.3.4. Cluster 4: pharmaceutical waste

From the waste management perspective, two main streams of pharmaceutical waste are (1) pharmaceutical wastes produced by households and in primary care treatment facilities, including unused, unwanted, or expired drugs or medicines with vials and syringes, and (2) pharmaceutical wastes, including at least one type of medical waste, generated by pharmacies, clinics, hospitals, and other healthcare and research facilities (Vallini and Townend, 2010; Voudrias et al., 2012). Environmental contamination in the wake of active ingredients in pharmaceutical waste has become an emerging global concern (Chung and Brooks, 2019) for the environment and eco-system, which calls for more preventive actions and inclusive environmental stewardship of pharmaceuticals.

Chung and Brooks (2019), in an in-street survey in Hong Kong with 1865 respondents, showed that 75% of the population has unneeded medicines at home. They also came to know that each household is storing on average 138.4 g of unnecessary medicines, of which the main type is medicines for cold. Based on their research, more than 53% of people dispose of unwanted or expired medicines in garbage cans along with the usual solid waste. This highlights the role of households as a primary source of pharmaceutical pollutants to affect environmental sustainability adversely. In another study to assesses the public perception of environmental effects caused by pharmaceutical waste in Malaysia, Ariffin and Zakili (2019) denoted that while 73.8% of the respondents believe that their household pharmaceutical waste should be separated from other households solid waste, only 25.2% return their unused or expired medicines through the medicine return-back programs. They highlighted an urgent need to develop effective return-back programs and channels for pharmaceutical waste, particularly household medicine waste, as a safer and environmentally sustainable disposal method to avoid posing hazardous risks to the environment and human health. To tackle the "pharmaceuticals in the environment" problem, Mitkidis and Mitkidis (2020) proposed to redesign current pharmaceutical takeback schemes and regulations to facilitate the interdisciplinary research collaborations between the fields of psychology, law, public health, and medical science to mitigate the problem. Moreover, the need for developing an integrated treatment system for pharmaceutical waste (Sarkar et al., 2019) and designing green, efficient, and scalable extraction platforms and separation methods to valorize the active pharmaceutical ingredients from pharmaceutical waste (Marić et al., 2021) have been highlighted as the current challenges faced towards sustainable pharmaceutical resource management.

4.3.5. Cluster 5: knowledge, attitude, and practice of HCW management

Healthcare facilities, such as hospitals, clinics, and nursing homes, as the main producers of HCW, are responsible for segregation, collection, in-site transportation, HCW pre-treatment, and HCW storage before such waste is collected by common HCW treatment facility operators (Gonibeedu et al., 2021). Therefore, training and monitoring programs on hazards linked to HCW to increase awareness and responsibility among healthcare personnel are crucial to implementing effective HCW practices and management. Gonibeedu et al. (2021), in a study to evaluate the knowledge, attitude, practice, and gaps in implementing the HCW practices in the primary healthcare facilities in India, showed that the efficiency scores of knowledge, attitude, and practice are 74% (good), 63% (average), and 54% (average), respectively. They highlighted the need for retraining all the personnel involved in the healthcare facility and periodically supportive supervision by health authorities to foster the implementation requirements. Parida et al. (2019) observed that while only 68% of healthcare workers in an Indian context know that the most important step in HCW management is waste segregation, only 49% of them correctly answer the questions regarding the associated hazards of HCW. Moreover, they found that laboratory waste handling is the least understood area of HCW management. In another survey to assess the awareness of biomedical waste management among dental students in Nepal, Singh et al. (2018) denoted that although the majority of the studied dental students (83.1% to 98.9%) have positive attitudes towards safe management of biomedical waste, more than half of them have no idea of the guidelines laid down by the Government. Including mandatory attendance in regular training workshops in the annual performance evaluation of all staff to increase compliance, in line with periodic monitoring, is the only way forward to reinforce knowledge, attitudes, and practices towards achieving sustainable HCW management (Parida et al., 2019). Woromogo et al. (2020) showed that a good level of knowledge among medical staff more likely leads to favorable attitudes towards HCW management. Besides, a good level of both knowledge and attitudes positively affects the associated HCW management practices, indicating the important role of knowledge and attitudes in successfully adopting HCW management policies and strategies. However, Mannocci et al. (2020) outlined the need for cross-sectional studies to develop a standardized and methodologically validated tool to assess the knowledge, attitude, and practices of healthcare professionals to better manage HCW activities. Due to the differences in national legislation, the healthcare industry settings, education systems, and cultural contexts, assessing the level of knowledge, attitudes, and practices regarding HCW management seems challenging and needs specific customizations on predesigned questionnaires.

5. Future research directions for HCW management towards a CE transition

In general, despite its potential to contribute to the CE transition, the healthcare industry has been overlooked in the CE discourse compared to other sectors, such as food, plastic, and manufacturing industries. This may be due to the single-use mindset of the healthcare industry setting in the wake of infectious, toxic, and hazardous nature of different HCW streams, which makes implementing CE strategies, such as "reuse", "recycle", and "recover" more challenging than ever.

In particular, based on the results provided in previous sections, potential research avenues for further research in the future regarding HCW management towards implementing a CE are presented in this section and summarized in Figure 7. Overall, three lines of research were identified to support the CE transition in the healthcare industry and HCW management context as follows:

- **Effective pharmaceutical waste management**

From the CE perspective, the pharmaceutical industry has been mainly focusing on reducing waste generation within the manufacturing processes over the recent years. In general, the pharmaceutical manufacturing sector, through the use of current sustainability models (e.g., environmental quotient, environmental factor, life cycle assessment, process mass intensity, and green chemistry model), has reduced waste generation (Ang et al., 2021). However, existing pharmaceutical waste research lacks a comprehensive study of the role of consumers and their consumption patterns towards implementing a CE in the pharmaceutical industry. As a result, developing a consumer-centric framework in line with CE principles highly deserves to be considered by researchers in future research to see how consumers could effectively contribute to pharmaceutical waste reduction. Hence, some potential directions would be (1) designing optimal return-back channels for expired medicines and (2) developing medicine sharing platforms under the required sanitary monitoring conditions for sharing unneeded or unwanted medicines among local communities to maximize the idle capacity (Ranjbari et al., 2018), prevent the households pharmaceutical waste generation, and increase the pharmaceutical resource efficiency.

- **Developing a CE transition framework for HCW management activities all together**

A few pieces of research regarding the adoption of a CE perspective for healthcare organizations have been conducted recently. For instance, Voudrias (2018) highlighted some steps that should be taken by healthcare facilities, including designing reusable items instead of single-use materials, adequately measuring waste production, and taking waste mitigation actions. Moreover, Chauhan et al. (2021) proposed a smart HCW disposal system enabled by industry 4.0

that takes CE perspectives into account. Nevertheless, putting an integrated CE model in place to deal with HCW as a whole is still lacking in the literature. A potential research direction for the future is designing, developing, and implementing a comprehensive CE transition model for HCW management as a whole, considering all activities involved within the waste hierarchy. In particular, the following five areas are recommended to be addressed in the future of the circular healthcare industry: (1) setting a clear agenda and drafting a CE-oriented healthcare industry action plan, (2) educating and, more importantly, activating healthcare facilities to change their routine from single-use mindset to embracing the CE transition, (3) optimizing healthcare asset sharing platforms among healthcare facilities, such as hospitals, clinics, and medical centers, (4) developing CE indicators for the healthcare industry to adequately measure and monitor the progress of HCW management strategies and actions towards establishing a circular healthcare industry, and (5) encouraging cross-sectional partnership among medical departments, healthcare manufacturers, reprocessing companies, and suppliers to (i) close, slow, or narrow healthcare supply chain loops, and (ii) develop reusing and reprocessing infrastructures towards achieving a CE.

- **Innovative solutions for creating circularity within the healthcare industry business model**

The complex issue of reusing and reprocessing healthcare materials, products, and instruments has been discussed in the waste management debate over recent years. On the one hand, disposable and single-use materials and products are widely used to control infection in the healthcare industry, increasing HCW generation. Replacing single-use products with reusable ones can significantly reduce the rate of HCW produced by healthcare facilities, particularly hospitals. For instance, Kwakye et al. (2011) denoted that a 1000-bed hospital is estimated to reduce 15,500 waste kg/year and save 175,000 US$/year only by using reusable sharp containers instead of disposable ones. On the other hand, although reprocessing of single-use products by healthcare facilities, which refers to reusing single-use products after repairing, cleaning, and sterilizing, could save costs and reduce waste, it faces many challenges, such as ethical, legal, and patient safety issues (Voudrias, 2018). The CE discourse in the healthcare industry is still in its infancy stage and highly needs more innovative approaches towards creating circularity and closing the loops in delivering high-quality healthcare services with fewer materials used and less HCW produced. Therefore, investigating innovative solutions for creating circularity within the business model and supply chain of the healthcare industry through policy incentives and technological advancements is recommended as another potential future research avenue. In this vein, three identified research areas to support the CE transition in the healthcare industry are: (1) technological and methodological advancements for safely recovering as much value as possible from HCW. Hence, various solutions should be developed and investigated at different scales to ensure maximal energy recovery from HCW streams. These solutions should be thoroughly scrutinized using advanced sustainability assessment tools, which have been effectively employed in various sectors of the waste management and valorization domain, such as life cycle assessment (Khoshnevisan et al., 2020; Rajaeifar et al., 2017), exergy analysis (Barati et al., 2017; Tabatabaei et al., 2021), exergoeconomic analysis (Aghbashlo et al., 2019b; Soltanian et al., 2019), and exergoenvironmental analysis (Aghbashlo et al., 2019a, 2018); (2) optimizing trade-offs between single-use and reusable healthcare materials, products, and instruments to replace as much single-use as possible with reusable ones to close the supply chain loops and maximize the healthcare resource efficiency; and (3) policy incentives to encourage financing in the HCW management sector and enforcing authorities' regulations to foster the CE transition, in particular within the context of developing countries.

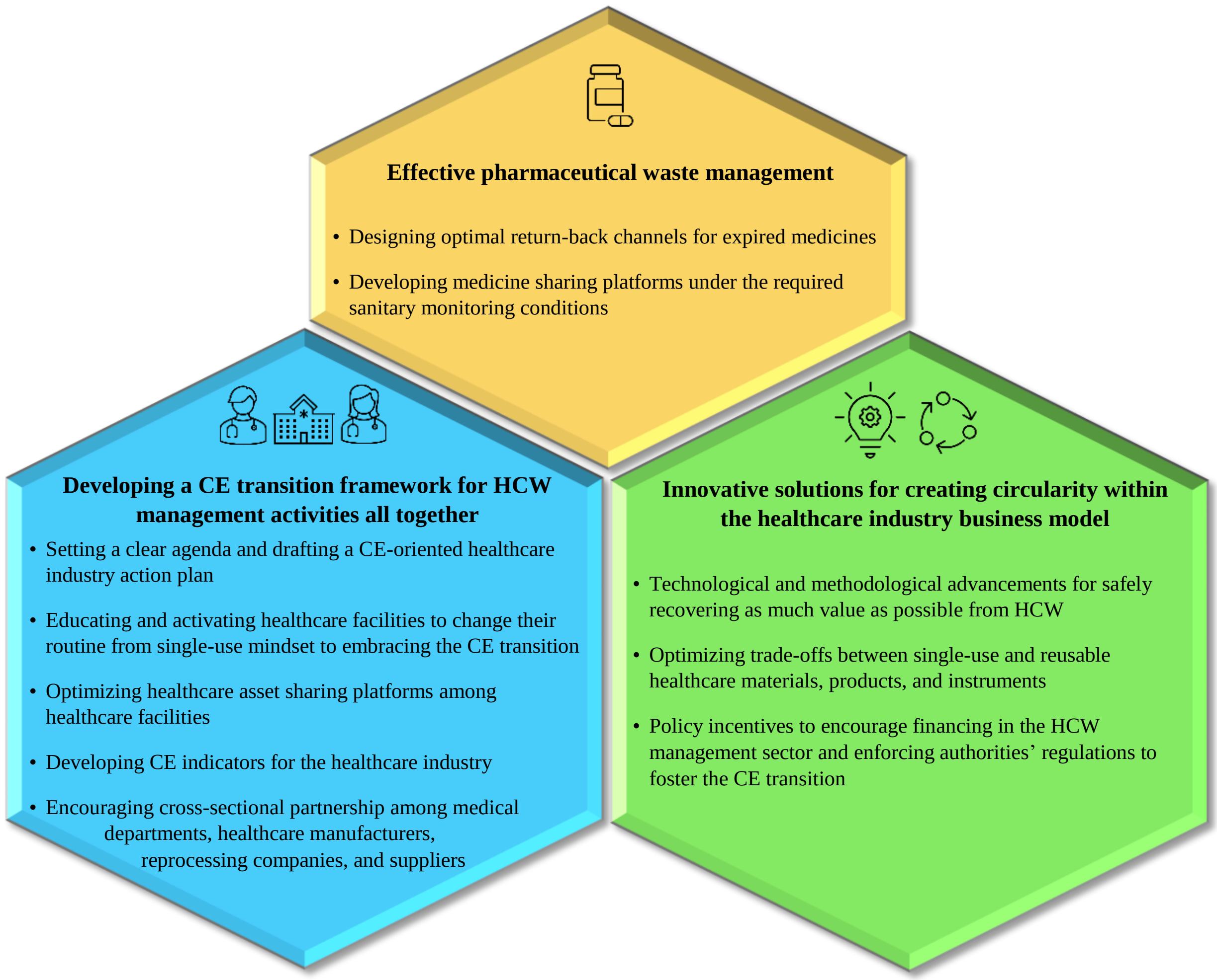

Fig. 7. Future research directions towards implementing a circular economy (CE) in the healthcare industry and healthcare waste (HCW) management.

6. Concluding remarks

The present research, as an attempt to map the past evolution and the current status of HCW research and discover its main research themes and trends, was conducted by following a mixed-method approach on 708 articles in WoS from 1985 to 2021. Having scrutinized the literature, our study particularly contributes to the existing body of knowledge of the HCW management domain by (i) providing a comprehensive overview of HCW management research and its associated research themes and trends, and (ii) identifying research gaps and proposing future avenues for research on sustainable HCW management towards implementing a CE within the healthcare industry.

Based on the results, four main research themes of HCW management were identified, including (1) HCW minimization, sustainable management, and policy-making, (2) HCW incineration and its associated environmental impacts, (3) hazardous HCW management practices, and (4) HCW handling, and occupational safety and training. Despite its great potential to contribute to the CE transition, the findings showed that the healthcare industry has been overlooked in the CE discourse compared to other industries, such as food, plastic, and manufacturing. This may be due to the single-use mindset of the healthcare industry settings in the wake of infectious, toxic, and hazardous nature of different HCW streams, which makes the implementation of CE strategies, such as "reuse", "recycle", and "recover" more challenging than ever. Three research avenues were provided for further research towards putting a CE in place for the healthcare industry and HCW management, including (i) effective pharmaceutical waste management through reduction of household pharmaceutical waste, (ii) developing a CE transition model for the healthcare industry and its associated HCW management practices and activities as a whole, and (iii) providing innovative solutions for creating circularity within the business model and also supply chain of the healthcare industry through policy incentives and technological advancements.

The theoretical/practical implications of this inclusive review for researchers, practitioners, and policy-makers involved in the healthcare industry and HCW management practices are outlined herein. Researchers and scholars are served by (i) rendering a comprehensive image of HCW management developments over time, (ii) identifying the most influential articles and journals that mainly have directed this field of study, (iii) mapping collaboration networks of contributing countries, institutions, and funding agencies, (iv) providing hotspots in the HCW management through employing keyword-based analyses, (v) unfolding prominent research themes and subject areas which have shaped the main body of knowledge in HCW management, and (vi) drafting a research agenda for the healthcare industry and accordingly HCW management in line with CE principles. For practitioners, policy-makers, and official authorities, the findings of the present study can be used as a guideline to (i) increase the understanding of different HCW management practices, from waste identification and prediction to waste disposal and incineration, and their impacts on the environment, human health, and workers safety, (ii) support implementing effective HCW management practices according to CE principles towards a cleaner and sustainable environment.

The present study is no exception to the limitations, which can be addressed for further developments. Firstly, the non-English research was excluded from the database used herein, although they may add more value to the obtained results and provided insights. Secondly, the WoS database was the only database of the current study, leading to missing some relevant research in this area. And finally, we employed bibliographic coupling as the data clustering technique to group the articles for conducting content analysis in this research. Applying other methods and algorithms to cluster articles might help improve the clustering results and, accordingly, content analysis for future studies.

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