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1 **Mapping healthcare waste management research: past evolution, current challenges, and future**
2 **perspectives towards a circular economy transition**

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29 **Abstract:**

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

45

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

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53 **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

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56 **1. Introduction**

57 As one of the fastest-growing global industries, the booming healthcare industry is increasingly
58 generating waste more than ever by providing a multitude of goods and services to control diseases
59 and treat patients (Kenny and Priyadarshini, 2021). The generated healthcare waste (HCW) can
60 highly affect environmental sustainability (Alharbi et al., 2021) and community health (Dang et
61 al., 2021). Furthermore, with an increase in population index and growth in healthcare facilities
62 (Thakur et al., 2021), the global generation of HCW follows a growth rate of 2–3%. The HCW
63 growth rate is even faster in China, which is expected to reach a volume of 2.496 million tons in
64 2023 (Li et al., 2021). Therefore, HCW, as a major environmental concern, needs proper
65 management and adopting suitable treatment strategies before final disposal to reduce its harmful
66 impacts (Alam and Mosharraf, 2020). In this vein, safe mechanisms to accurately segregate,
67 collect, transport, treat and dispose of HCW are pivotal for HCW management to ensure
68 environmental protection and socio-economic sustainability. However, properly implementing
69 HCW management policies is facing many challenges, such as lack of budget allocation by the
70 hospital administration, unskilled workers handling the infectious waste, and outdated
71 technologies and methods used to dispose of HCW (Thakur et al., 2021). For instance, according
72 to the assessment provided by the World Health Organization (WHO) in 2015, only 58% of the
73 sampled facilities from 24 countries all around the world had proper systems to deal with the safe
74 disposal of HCW (WHO, 2015a).

75 A tremendous amount of research on different streams of HCW has been carried out over the
76 last decade. Efforts within the existing literature have been mainly focused on but not limited to
77 perceived risk and associated factors of HCW (Karki et al., 2020), developing indicators for HCW
78 management (Barbosa and Mol, 2018; Ferronato et al., 2020), hazardous medical waste (Komilis

79 et al., 2012; Marinković et al., 2008), HCW incineration (Anastasiadou et al., 2012; Gidarakos et
80 al., 2009), sustainable environmental management of HCW (Alharbi et al., 2021), HCW treatment
81 technologies (H. Li et al., 2020), and more recently, HCW management challenges during the
82 COVID-19 pandemic (de Aguiar Hugo and Lima, 2021). Although delivery of high-quality care
83 is the main priority for the healthcare industry, waste minimization and preparation for reuse,
84 recycling, and recovery programs based on the circular economy (CE) model should be considered
85 to save both environmental and financial resources (Voudrias, 2018). Nevertheless, the literature
86 lacks a comprehensive understanding of how a CE model can take in place to deal with HCW due
87 to its infectious and hazardous nature, which poses a serious threat to the environment and human
88 health. On the other hand, the outbreak of the COVID-19 pandemic has even made the disposing
89 of HCW in a sustainable manner more complicated, with highly infectious waste coming from
90 patients and healthcare workers (Chauhan et al., 2021). Moreover, due to the fragmented literature
91 of HCW research, an inclusive framework of HCW research themes and trends towards a CE
92 transition and sustainable environment is still blurred, calling for more investigation.

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

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

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

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

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

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

116

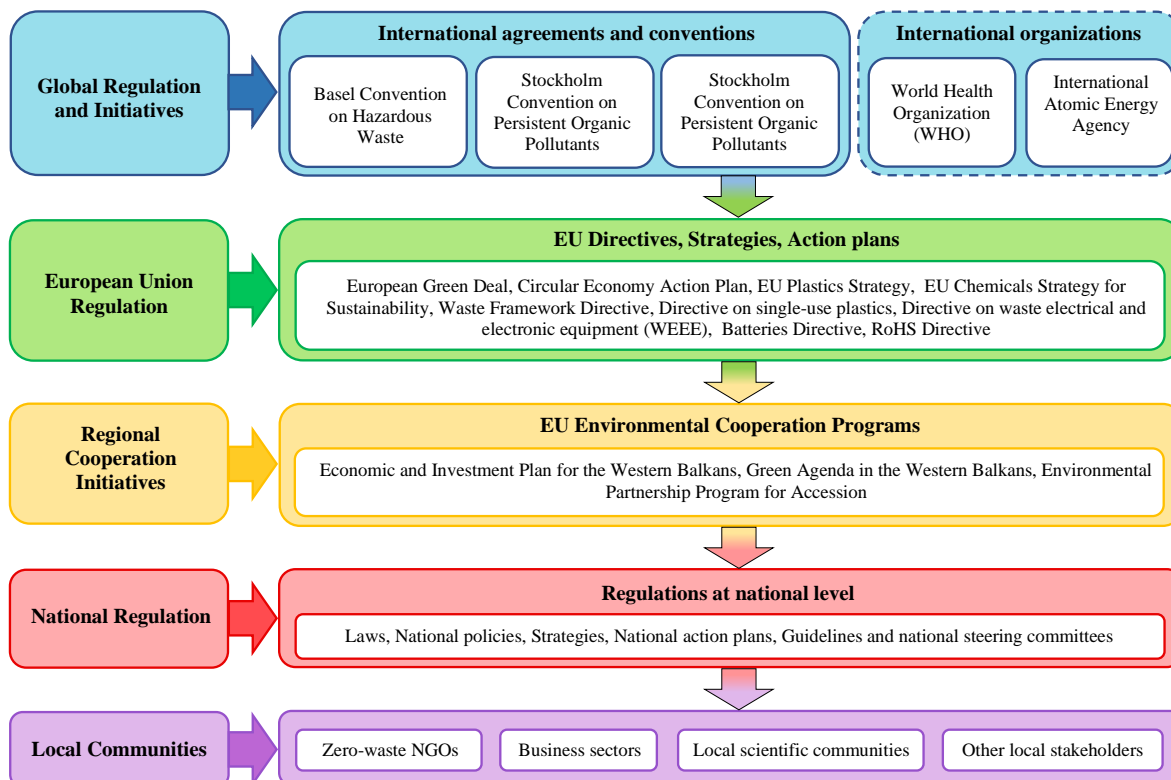
117 **2. Healthcare waste streams: an overview**

118 The concept of HCW refers to any waste generated through the process of delivering
119 healthcare services by healthcare facilities, such as hospitals and clinics, or in any other place by
120 individuals or households. A diversity of classifications exists for HCW, mainly dividing the total
121 stream into hazardous and non-hazardous fractions, representing 75–90% and 10–25% of the total
122 HCW, respectively (WHO, 2014), as illustrated in Figure S1 in Supporting Information. Non-
123 hazardous fraction of HCW, also known as general HCW, is usually similar to municipal solid

124 waste and includes paper, plastic, glass, and food residues and containers, generated mainly from
125 the kitchen, administrative, and housekeeping activities within the healthcare facilities (Oduro-
126 Kwarteng et al., 2021). In contrast with non-hazardous waste that does not result in any particular
127 chemical or physical hazard, the hazardous fraction of the HCW may result in a range of
128 environmental and health risks (Domingo et al., 2020). The hazardous HCW is classified into
129 different categories according to the type, source, and risk factors related to its handling, transport,
130 storage, and final disposal (WHO, 2017). This waste stream includes sharps, infectious waste,
131 obsolete or expired chemical products, pharmaceuticals, anatomical and pathological waste, and
132 radioactive waste (UN, 2011). Notably, the disposal costs of hazardous wastes are ten times more
133 than non-hazardous waste (Amariglio and Depaoli, 2021). Therefore, when reporting HCW
134 generation rates, adequately identifying the types and quantities of HCW produced is significantly
135 crucial in proper and safe HCW management (Minoglou et al., 2017).

136 The WHO and International Atomic Energy Agency have elaborated some policy documents
137 and guidelines to support countries in implementing better HCW management systems (UN,
138 2011). Furthermore, many countries have signed and ratified such international conventions as
139 Basel Convention on Hazardous Waste, Stockholm Convention on Persistent Organic Pollutants,
140 and Minamata Convention on Mercury. In addition, most of the developed countries adopted
141 national legislative and administrative regulations to create a sustainable HCW management
142 system (Rizan et al., 2021). Figure 1 summarizes the various levels of HCW governance with a
143 focus on European Union countries. Obviously, in line with the global agreements and conventions
144 set by the WHO and the International Atomic Energy Agency, European Union has also laid
145 several legislations, directives, strategies, and action plans to improve waste management practices
146 in Europe, part of which refers to HCW. These directives and action plans include but are not

147 limited to the Waste Framework Directive (European Council, 2008), European Green Deal
 148 (European Commission, 2019), Circular Economy Action Plan (European Commission, 2015),
 149 and Directive on single-use plastics (EU, 2019). Furthermore, at the regional level, the European
 150 Commission has adopted an Economic and Investment Plan for the Western Balkans (European
 151 Commission, 2020a) and the Green Agenda in the Western Balkans (European Commission,
 152 2020b) to support the green recovery of the countries of the region. Furthermore, as a regional
 153 cooperation program, the Environmental Partnership Program for Accession was funded by the
 154 European Union for a duration of three years (2019–2022) to support the development in
 155 environmental governance in the Western Balkans and Turkey (EU, 2020). These initiatives are
 156 followed by laws, policies, strategies, action plans, guidelines, and steering committees at the
 157 national level in each country and are considered and followed by local communities, including
 158 zero-waste NGOs, business sectors, local scientific communities, and other local stakeholders.



159 **Fig. 1.** Various levels of healthcare waste (HCW) governance with a focus on European Union countries.
 160

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

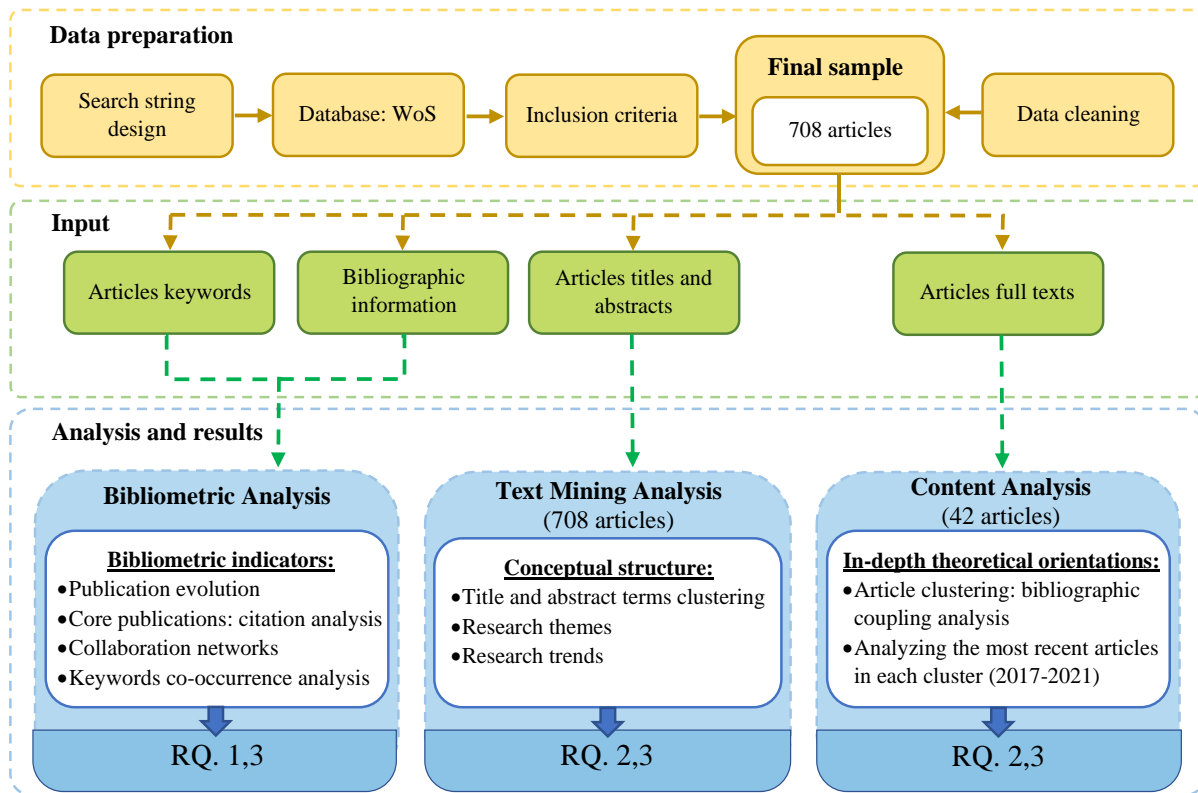
171 The CE has been introduced in the literature as a potential approach to reduce the negative
172 environmental impacts of the HCW (Kane et al., 2018; van Straten et al., 2021). The CE approach
173 refers to a regenerative system in which, through slowing, closing, and narrowing supply chain
174 loops, material input, waste, and emissions are minimized (Geissdoerfer et al., 2017). Accordingly,
175 the design framework for the CE is increasingly used in industry to build up product circularity in
176 terms of its multiple-use and recycling (Linder et al., 2020; Shevchenko et al., 2021) and product
177 sustainability in terms of minimizing its negative impact on the environment (Dyllick and Rost,
178 2017). Some limited CE practices already exist within the HCW management system in various
179 forms and maturity levels (Kane et al., 2018). For instance, the CE approach has been highlighted
180 in the literature as a means of reducing HCW through reusing and recycling durable medical
181 equipment (Ordway et al., 2020), repairing and recycling hospital instruments and surgical
182 stainless steel wastes (van Straten et al., 2021), and replacing disposable products with reusable
183 ones in medical and dental sectors (Antoniadou et al., 2021). Besides, recovering value from

184 disposables, such as using medical needles in concrete production, has also been stressed in the
185 existing studies (Hamada and Ismail, 2021). However, there is a lack of decent academic
186 discussion regarding the application of CE principles and practices to increase resource efficiency
187 in the healthcare industry and reduce the adverse environmental effects of both hazardous and non-
188 hazardous HCW.

189

190 **3. Research design**

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



199 **Fig. 2.** Research framework adopted for mapping healthcare waste (HCW) management research from 1985 to
 200 2021.
 201

202

203 3.1. Data collection and preparation

204 The Web of Science (WoS) database, as one of the most trusted publisher-independent
 205 global citation databases in academia, was selected for collecting data herein. A combination of
 206 different keywords directly addressing the scope of our study was extracted from literature and
 207 elaborated to design the following search string: "healthcare waste" OR "medical waste" OR
 208 "hospital waste" OR "clinical waste" OR "infectious waste" OR "sharps waste" OR "pathological
 209 waste" OR "pharmaceutical waste" OR "biomedical waste" (search in the title of articles) AND
 210 "environment*" OR "sustainab*" OR "circular economy" OR "circularity" OR "closed loop" OR
 211 "reduc*" OR "reus*" OR "recycl*" OR "hazard*" OR "manag*" (search in the title, abstract,
 212 author keywords, and keywords plus of articles). Only peer-reviewed journal articles in the English

213 language were considered (i.e., conference proceedings, editorial, reports, book chapters, etc.,
214 were excluded) with no time limit. The search process was started in early March 2021 and stopped
215 on June 4, 2021, with a final sample consisting of 708 articles. Table S1 in Supporting Information
216 summarizes the search protocol.

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

228

229 **3.2. Data analysis**

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

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

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

257

258 **4. Results and Discussion**

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

264

265 **4.1. Findings of the bibliometric analysis**

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

270

271 **4.1.1. Chronological distribution of publications**

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

279

280 4.1.2. Analysis of core journals

281 With respect to the source journals, the 708 articles of our sample have been published in
282 314 journals indexed in WoS. Among all the 314 journals, 224 journals only published one article.
283 The top ten most productive journals in terms of the number of publications in the HCW research
284 domain, accounting for 32.2 % of the total published articles in our database (228 out of 708), are
285 presented in the upper part of Figure 3**Error! Reference source not found.** Based on the results,
286 *Waste Management & Research* is the most productive journal with 81 articles, and therefore,
287 plays a significant role in the HCW research domain. The second and third most productive
288 journals are *Waste Management* and *Fresenius Environmental Bulletin* with 52, and 17
289 publications, respectively.

290 The number of articles published by each of the mentioned top ten most productive journals
291 during the recent five years (2017–2021) is shown in Figure S3 in Supporting Information. *Waste*
292 *Management & Research*, the leading journal in terms of the publications number in the whole
293 dataset, has followed a growing trend within the recent 5-year period and has managed to be the
294 leading journal within this period. Conversely, *Waste Management*, the second most productive
295 journal in our dataset, has not shown a growth rate in terms of productivity during the past five
296 years, despite publishing five articles in 2017–2021. Besides, although *Journal of Hazardous*
297 *Materials* and *Journal of Hospital Infection* are ranked 7th and 8th productive journals, respectively,
298 they have had no record of publication from 2017 onwards in our database. However, a jump could
299 be observed in terms of the number of publications by *Journal of Cleaner Production* in 2021, and
300 a considerable increase in the number of publications by *Fresenius Environmental Bulletin* in
301 2019 and 2020.

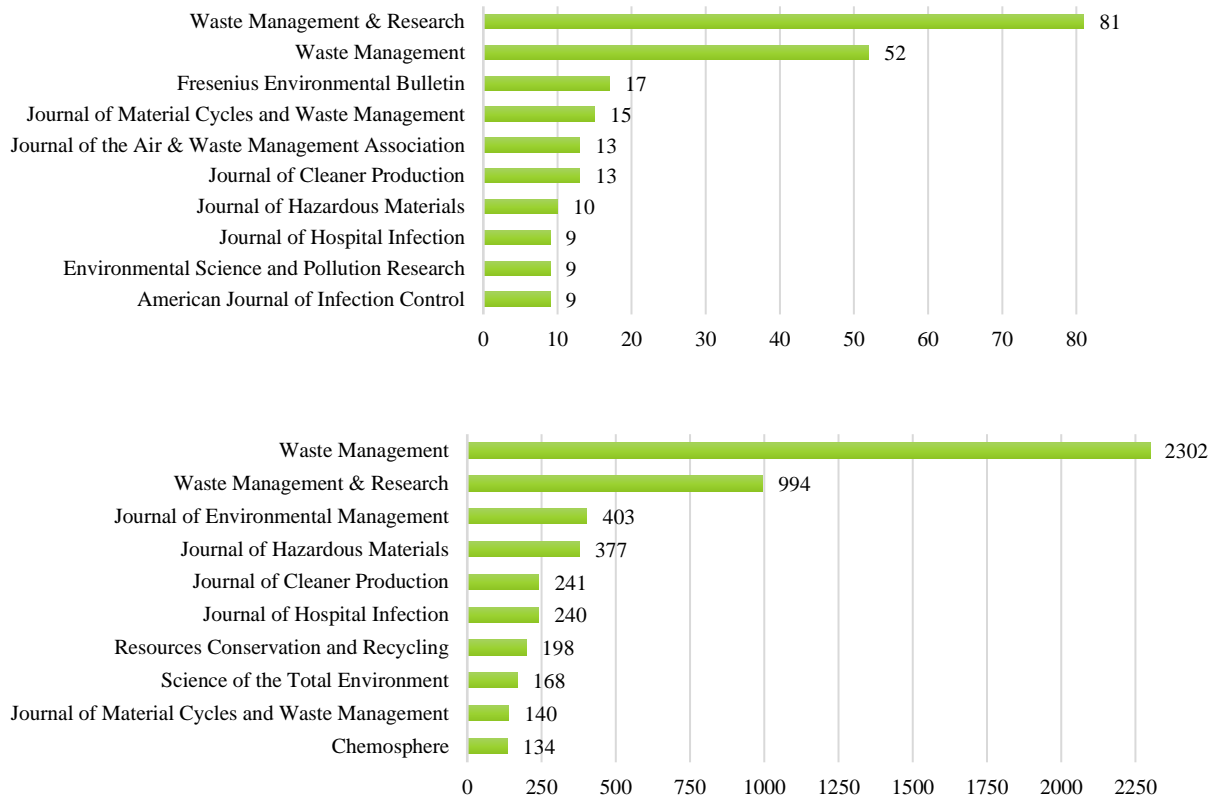
302 Figure S4 in Supporting Information shows the publication trend of the journals with at
303 least five articles in the period 2017–2020 in our dataset. Reappearing *Waste Management &*
304 *Research*, *Waste Management*, *Fresenius Environmental Bulletin*, *Environmental Science and*
305 *Pollution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

313 On the other hand, the lower part of Figure 3 **Error! Reference source not found.** shows
314 the top ten most influential journals regarding the number of citations they have gained until June
315 2021 based on the WoS database. *With a total of 2302 citations*, *Waste Management* is the most-
316 cited journal, attracting the great attention of scholars in the HCW research area. The following
317 influential journals are *Waste Management & Research*, *Journal of Environmental Management*,
318 and *Journal of Hazardous Materials* with 994, 403, and 377 total citations, respectively.

319

320

321



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

324

325 4.1.3. Influential articles

326 The number of citations to scientific articles could be used to measure their influence on
 327 the related research area (Merigó et al., 2015). Table S2 in Supporting Information lists the top ten
 328 most influential articles within the HCW research domain in our dataset. As shown in Table S2,
 329 the most influential article with 135 citations is an inclusive review paper conducted by Windfeld
 330 and Brooks (2015) that has provided an overview of medical waste management practices focusing
 331 on the common sources, governing legislation, and handling and disposal methods. Consistent
 332 with the previous article, Jang et al. (2006) carried out the second highly cited article with 130
 333 citations to present an image of the current medical waste management practices considering

334 generation, composition, segregation, transportation, and disposal of HCW in Korea. A system
335 dynamics modeling research developed by Chaerul et al. (2008) is ranked the third among
336 influential articles, which has determined the interaction among factors in the HCW system,
337 highlighting the importance of proper waste segregation and infectious waste treatment prior to
338 disposal in developing countries. Suitable toxicity evaluation of HCW (Tsakona et al., 2007) and
339 the issues regarding safe management of hazardous medical waste generated by hospitals
340 (Marinković et al., 2008) are also included in the most influential articles. Moreover, among the
341 top ten most influential articles, Iranian authors with two case studies from Iranian hospitals were
342 ranked fourth (Askarian et al., 2004) and tenth (Taghipour and Mosaferi, 2009), focusing on the
343 characterization of HCW. The Journal *Waste Management* with six influential articles out of ten
344 has a considerable contribution to the HCW research.

345

346 **4.1.4. Collaboration network analysis and funding agencies**

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

352 As shown in Figure S5 in Supporting Information, India with 108 HCW-related articles is
353 placed in the topmost position of productive countries. India is closely followed by China as the
354 second most productive country with 107 articles. In this vein, the USA, Iran, England, and Turkey
355 are the following productive countries with 59, 50, 48, and 35 HCW-related research, respectively.
356 Moreover, with respect to the number of collaborations with other countries, China with 44

357 international collaborations (mostly with Pakistan, the USA, England, and Japan) is ranked first.
358 England with 33 and India with 26 international links come next as the second and third most
359 collaborative countries. On the contrary, Taiwan with one and Greece and Brazil with three links
360 have the lowest level of collaboration among the top ten countries in the list.

361 The results show that developing countries have had a considerable role in constructing the
362 body of knowledge in the HCW research, since six out of the top ten productive countries are from
363 these countries, including India, China, Iran, Turkey, Brazil, Pakistan, and Taiwan. Nevertheless,
364 HCW management in developing countries has not received sufficient attention (Abd El-Salam,
365 2010), and many of these countries still suffer from inappropriate medical wastes disposal and
366 treatment methods. This issue may be due to the lack of required infrastructure, technological
367 advancements, budget, regulation, and legislative enforcement. However, the gap between high
368 scientific HCW-related production in academia and low adaptation of suitable HCW strategies in
369 practice to take a sound HCW management system in place could be an issue of debate for more
370 investigation within the context of developing countries.

371 In terms of institutional contribution, a total of 929 institutions in our database have
372 conducted research in the HCW context. To illustrate the collaboration network among
373 institutions, the largest set of connected institutions consisting of 123 unique institutions were
374 plotted, as shown in Figure S6 in Supporting Information. Chinese Academy of Sciences with 16
375 articles and Zhejiang University with 14 articles both from China, and Tehran University of
376 Medical Sciences with 13 articles from Iran are the most productive institutions in HCW research.
377 Moreover, the top three actively collaborating organizations in the studied database are Tehran
378 University of Medical Sciences, Chinese Academy of Sciences, and University of Northampton
379 with 23, 22, and 19 collaboration links, respectively. Iranian institutions appeared as the leading

380 organizations in shaping the literature of HCW-related research since four institutions out of the
381 top ten contributing institutions are from Iran. Tehran University of Medical Sciences is notably
382 highlighted as the first institution in terms of the number of collaboration links with other
383 institutions and the third institution in terms of the number of contributions.

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

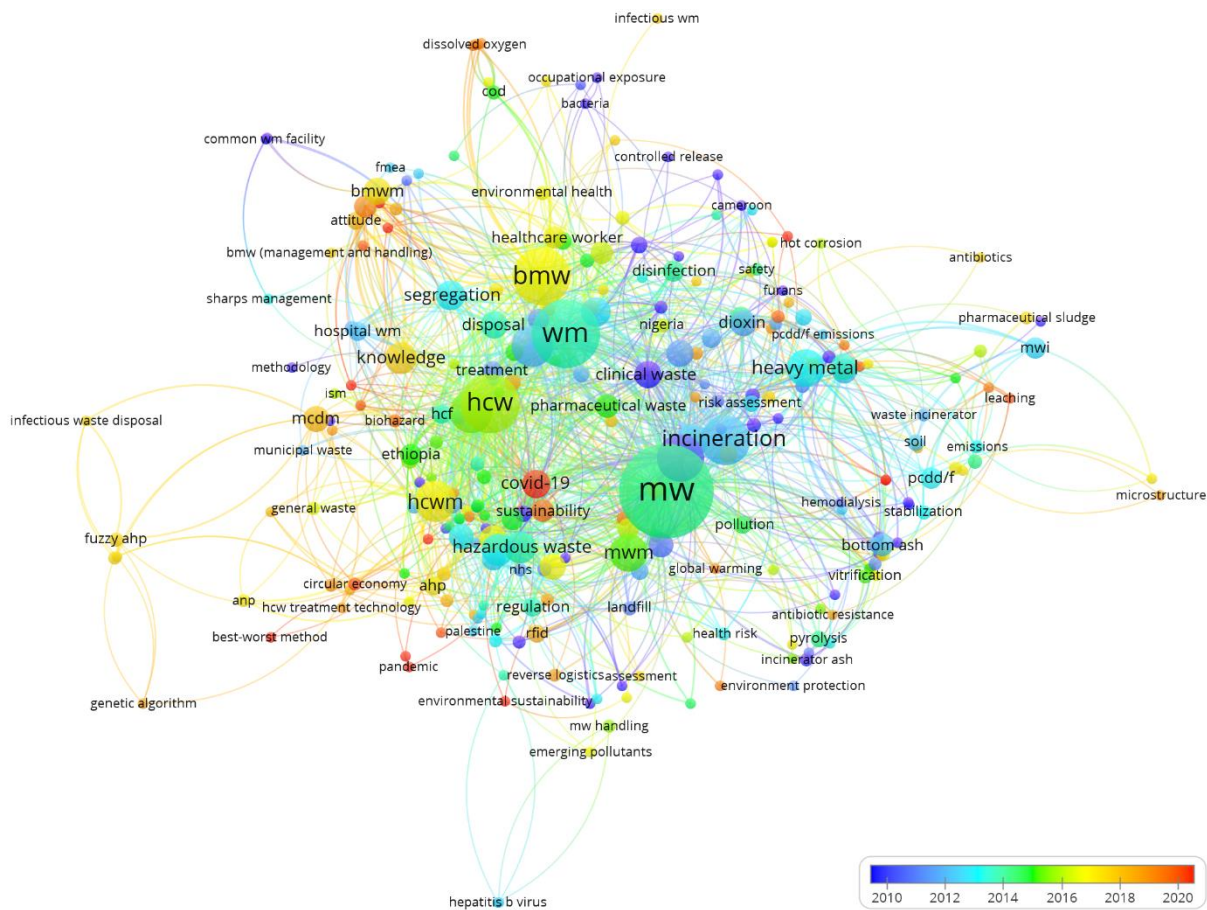
402

403 **4.1.5. Keywords co-occurrence analysis**

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

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

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



433
 434 **Fig. 4.** Co-occurrence network of the keywords within the healthcare waste (HCW) research.

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

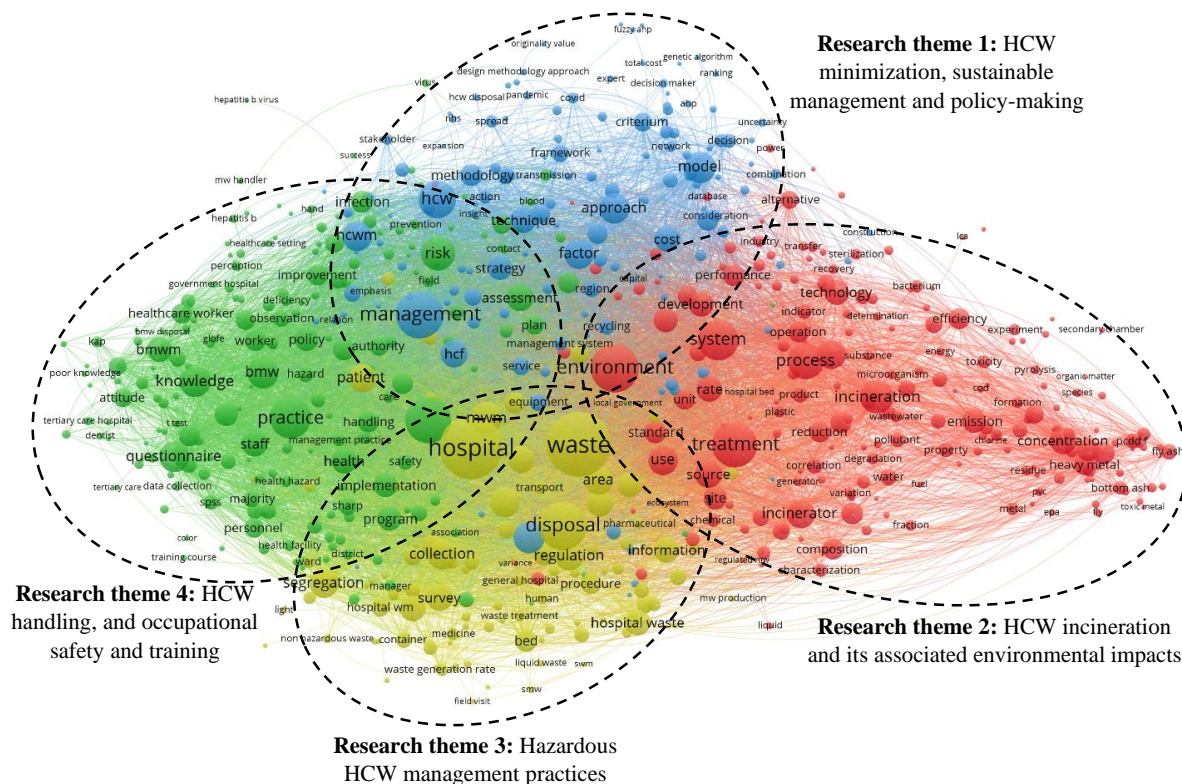
443 The top 20 most frequent pairs of keywords that most co-occurred in HCW research are
444 listed in Table S4 in Supporting Information. The link between the medical waste and waste
445 management nodes in the co-occurrence network is the most prominent co-occurrence link with a
446 strength score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

458

459 **4.2. Text mining analysis: identifying salient research themes**

460 Having conducted a text mining analysis on the concatenation of the titles and abstracts of
461 all 708 articles, a total of 14,578 terms was detected. According to the relatedness of the terms
462 based on a co-occurrence links algorithm, the extracted terms were clustered. A threshold of at
463 least five occurrences of terms was applied for more visibility of the identified themes and their
464 associated terms. As a result, four main HCW research themes were discovered, including: (i)
465 HCW minimization, sustainable management, and policy-making, (ii) HCW incineration and its

466 associated environmental impacts, (iii) hazardous HCW management practices, and (iv) HCW
 467 handling, and occupational safety and training. Figure 5 visualizes the conceptual structure of
 468 HCW research and its four main research themes in the literature. Moreover, a sample of the most
 469 relevant terms included in each research theme and also some recent exemplary references are
 470 provided in Table 1.



471 **Fig. 5.** Visualization of the main identified research themes of healthcare waste (HCW) research in the literature.
 472
 473

474 **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	Tirkolae 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)

475

476 One of the four identified dominant HCW research themes is "modeling approaches
477 towards HCW minimization, sustainable management, and policy-making". The studies
478 corresponding to this research theme have been mainly focused on the optimization issue for
479 increasing the performance of HCW management systems, such as routing optimization for urban
480 medical waste recycling networks (Gao et al., 2021) and infectious waste disposal methods
481 (Wichapa and Khokhajaikiat, 2017). On the other hand, multi-criteria decision-making methods
482 have been widely employed within the first research theme for different purposes, such as
483 developing assessment models for HCW disposal (Geetha et al., 2019) and choosing proper
484 locations for infectious waste disposal as a critical issue in hazardous waste management to
485 decrease the risk imposed on the environment (Wichapa and Khokhajaikiat, 2018). Moreover,

486 optimization methods have been found useful in HCW management during the COVID-19
487 pandemic through (1) developing cooperative models for the collection of infectious waste
488 generated due to the pandemic (Valizadeh and Mozafari, 2021), (2) sustainable multi-trip location-
489 routing problems for medical waste management during COVID-19 (Tirkolaei et al., 2021), and
490 (3) reverse logistics network design for medical waste management after COVID-19 (Kargar et
491 al., 2020).

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

509 and microwave disinfection in the HCW treatment (Mahdi and Gomes, 2019), and (5) the
510 quantities and characteristics of pollutants emitted during the incineration of medical waste (Ma et
511 al., 2020; Zhang et al., 2020).

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

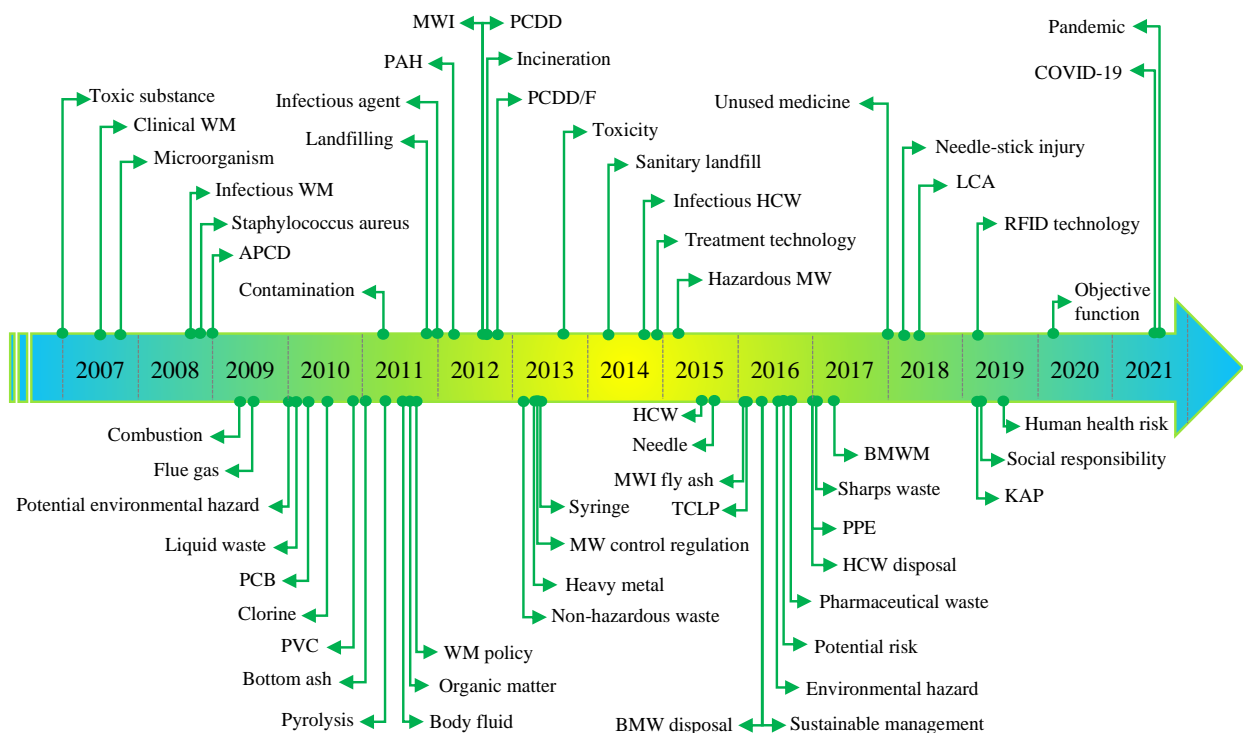
528 The last identified HCW research theme is "HCW handling and occupational safety and
529 training", which refers to awareness and adequate knowledge about safe and proper handling and
530 disposal of infectious and hazardous HCW. The sufficient knowledge and practice of healthcare
531 workers to sustainably deal with HCW and its potential risks are indispensable to perform any

532 effective HCW management system (Akkajit et al., 2020). The effectiveness of educational
533 intervention programs based on the knowledge, attitude, and practices (KAP) framework on
534 hospital waste management (Abdo et al., 2019) and assessing the impact of educational training
535 on the behavioral intention for HCW management (Robat et al., 2021) have mainly constructed
536 the body of knowledge of this research theme. Moreover, developing a KAP model for
537 implementing biomedical waste management practices in primary healthcare facilities (Gonibeedu
538 et al., 2021) and for reflecting the inadequacies in existing HCW management practices (Behnam
539 et al., 2020) has been widely considered.

540 The evolution of the selected main subject areas and research topics within the identified
541 HCW research themes over the recent years is mapped in Figure 6, considering their average
542 publication year. Average publication year calculated based on a binary counting of the terms
543 refers to the average publication year of all the documents that contain a specific term in their titles
544 or abstracts. Therefore, more than one occurrence of a term in an article's title and abstract does
545 not result in a higher weight for the article in the average calculation. Considering the growth of
546 the number of articles on HCW as previously illustrated in Figure S2 in Supporting Information,
547 since the number of articles has notably increased after 2006, the average publication year of the
548 main terms in this field usually appears after 2006. As illustrated in the timeline in Figure 6,
549 research topics such as life cycle assessment, needle-stick injury, human health risk, social
550 responsibility, objective function, KAP, radio frequency identification technology, and COVID-
551 19 have been attracting attention very recently, since their average publication year is between
552 2018 and 2021. Based on the results, COVID-19 and pandemic have been appeared as the most
553 recent research topics with an average publication year of 2020.647 and 2020.7, respectively. This
554 result is due to the recentness of COVID-19 and the surge of research to respond to the urgent call

555 for action against the pandemic (Ranjbari et al., 2021c, 2021a). Subject areas focusing on unused
 556 medicine, biomedical waste management, sharps waste, personal protective equipment, healthcare
 557 disposal, pharmaceutical waste, environmental hazards, medical waste incinerator fly ash,
 558 treatment technology, infectious HCW, sanitary landfill, and toxicity have been located in the
 559 average publication year period of 2013 to 2017. Moreover, incineration, polycyclic aromatic
 560 hydrocarbon, infectious agent, landfilling, waste management policy, body fluid, bottom ash,
 561 pyrolysis, liquid waste, and combustion have been less attracting attention during the recent years
 562 with an average publication year before 2013.

563



564

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

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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.

574 **4.3. Content analysis**

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

585

586 **Table 2.** Selected most recent research within main clusters of healthcare waste (HCW)-related articles from 2017
 587 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)	Çetinkaya et al. (2020)	Liu et al. (2019)	Chung and	Gonibeedu et al.
Homayouni and	Ali et al. (2017)	Ethica et al. (2018)	Brooks (2019)	(2021)
Pishvae (2020)	Hasan and Rahman	Trebooniti (2021)	Ariffin and	Parida et al. (2019)
Gao et al. (2021)	(2018)	Zhang et al. (2020)	Zakili (2019)	Singh et al. (2018)
Yao et al. (2020)	Gunawardana (2018)	Li et al. (2017)	Mitkidis and	Woromogo et al.
Torkayesh et al.	Yousefi and Avak	Ma et al. (2020)	Mitkidis (2020)	(2020)
(2021)	Rostami (2017)	Qin et al. (2018)	Sarkar et al.	Mannocci et al.
Nikzamir et al. (2020)	Santos et al. (2019)	Y.-M. Li et al.	(2019)	(2020)
Yu et al. (2020)	Mmerekki et al. (2017)	(2020)		
Hinduja and Pandey	Wilujeng (2019)	Ababneh et al.		
(2018)	Eslami et al. (2017)	(2020)		
Narayanamoorthy et	Khan et al. (2019)	Shen et al. (2019)		
al. (2020)	Barbosa and Mol	Samad et al. (2019)		
H. Li et al. (2020)	(2018)	Pant (2018)		

588

589 **4.3.1. Cluster 1: the application of modeling methods for effective HCW management**
590 **systems**

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

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

624

625 **4.3.2. Cluster 2: HCW management practices**

626 Mismanagement of HCW owing to its potential hazard can significantly pose
627 environmental and occupational health risks to the global community. However, implementing
628 effective HCW management practices is not straightforward due to the complexity of its health
629 and environmental effects, economic aspects, and social impacts (Çetinkaya et al., 2020). For
630 instance, Ali et al. (2017) highlighted the main challenges faced by hospitals in developing
631 countries, including (1) suffering from inadequate waste segregation, collection, storage,
632 transportation, and disposal practices, (2) HCW management regulations and legislations lagging
633 behind (which varies from one hospital to another), and (3) the absence of decent training programs
634 for hospital staff. In a survey in Bangladesh, Hasan and Rahman (2018) stated that 56% of hospital

635 workers do not receive any form of training to deal with hazardous waste, and 54% of them do not
636 use any safety equipment or clothing. Besides, a suitable approach to select an effective HCW
637 treatment technology, particularly for treating hazardous waste, is still challenging for municipal
638 authorities (Hasan and Rahman, 2018). Gunawardana (2018), in an empirical analysis of 156
639 healthcare service providers in Sri Lanka, outlined an urgent need for training the top managers
640 involved in the healthcare industry to create a positive attitude towards adopting new HCW
641 treatment technologies and trends.

642 Proper actions regarding HCW identification, prediction, segregation, collection,
643 transportation, and disposal in hospitals could control putting the worker's safety at risk. The
644 importance of timely and precisely determining the quantity and quality of infectious HCW was
645 highlighted by Yousefi and Avak Rostami (2017) in effective HCW management systems.
646 Moreover, sustainable HCW management could be implemented only if an adequate waste
647 generation prediction is made; otherwise, investment in this sector would be inefficient (Çetinkaya
648 et al., 2020). In this context, Santos et al. (2019), in a study to evaluate the HCW management in
649 a Brazilian context, showed that more than 55.6% of the generated HCW is general waste, followed
650 by infectious, sharps, and chemicals wastes, with the shares of 39.1%, 2.9%, and 2.4%,
651 respectively. Mmereki et al. (2017) showed that current HCW collection and storage facilities in
652 Botswana in Africa do not operate efficiently, and more focus should be on the segregation of
653 infectious and non-infectious from general waste, pollution prevention, and recovery of valuable
654 materials from healthcare facilities. In another study conducted in 17 representative clinics in
655 Indonesia, Wilujeng (2019) denoted that segregation, collection, and storage of the waste
656 generated by clinics, comprising of 21% sharps, 42% infectious, and 37% general waste, did not
657 comply with the government regulatory standard. Eslami et al. (2017) reported that 14.8% of

658 private hospitals and 24.29% of government hospitals in Iran lack any treatment devices, and
659 hazardous HCW is disposed of without any treatment, showing poor hazardous treatment services.
660 Khan et al. (2019) highlighted the need for replacing outdated incineration plants with autoclaving,
661 steam sterilization, and new practices of pyrolysis to avoid the emission of toxic gases in the Asian
662 developing countries, which lack proper waste segregation, collection, storage, transportation, and
663 disposal. Developing HCW indicators to continuously monitor, handle, and manage HCW
664 generation and its associated risks significantly improves HCW risk management (Barbosa and
665 Mol, 2018) and HCW operation systems from identification at the beginning to the disposal at the
666 end.

667

668 **4.3.3. Cluster 3: HCW treatment technologies and methods**

669 Implementing effective HCW management practices to a large extent is determined by the
670 treatment technology applied. The application of an HCW technology, which is simultaneously
671 inexpensive (Liu et al., 2019) and environmentally friendly (Ethica et al., 2018), has been a subject
672 of research interest over recent years. According to the study conducted by Jang et al. (2006),
673 HCW treatment technologies such as steam sterilization, chemical disinfection, microwave
674 sanitation, recycling, reverse polymerization, dry heat disinfection, autoclaving, and incineration
675 are considered as alternatives. Some studies highlight that due to the advantages of the incineration
676 method, for instance, destruction of bacteria or viruses, reduction of the waste volume, and the
677 potential for energy reuse, many countries incinerate HCW (Trebooniti, 2021; Zhang et al., 2020).
678 Moreover, incineration is used to dispose of 59–60% of the general HCW worldwide (Li et al.,
679 2017; Zhang et al., 2020). However, the medical waste incinerator is considered a key source of
680 hypertoxic PCDDs and PCDD/Fs emission and heavy metals according to Stockholm Convention.

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

683 To avoid secondary pollution, the academic discussion is still ongoing with a focus on the
684 emission characteristics of PCDD/Fs and heavy metals resulting from the incineration (Ma et al.,
685 2020; Zhang et al., 2020), technologies for the reduction of the emission (Li et al., 2017; Qin et
686 al., 2018), and techniques to remove (Y.-M. Li et al., 2020) or reduce the concentration of heavy
687 metals from the medical waste fly ash (Ababneh et al., 2020; Shen et al., 2019) or detoxify the fly
688 ash (Liu et al., 2019). In particular, various treatment techniques for medical waste fly ash and
689 their merits, demerits, applicability, and limitations have been reviewed by Liu et al. (2018). An
690 effective circulating system based on using EDTA disodium (Na_2EDTA) was developed by Y.-
691 M. Li et al. (2020) to remove Cu, Pb, Zn, Cd, and Ni from medical waste fly ash. Shen et al. (2019)
692 proposed a technology to reduce dioxin formation during the incineration process based on using
693 activated carbon, which adsorbs dioxin and pelletizes it with adhesive material. The treatment
694 technology for medical waste incinerator fly ash, which is considered hazardous, to simultaneously
695 detoxify both PCDD/Fs and heavy metals through a successive flotation process was proposed by
696 Liu et al. (2019). Exploring the possibilities of medical waste fly ash recycling in mortar mixtures,
697 Ababneh et al. (2020) proposed using ethylene diaminetetra acetic acid disodium as a chelating
698 agent allowing the reduction of the heavy metals concentration in medical waste fly ash. In
699 addition, the study by Anastasiadou et al. (2012) demonstrated the feasibility of using fly and
700 bottom ash in cement matrices to dispose of them safely in non-hazardous landfills or even to reuse
701 these materials in the construction industry. Another line of studies in academia considered
702 hospital wastewater and focused on the pollution of the groundwater near the biomedical waste
703 treatment facilities (Samad et al., 2019), migration of heavy metals from the biomedical waste

704 autoclave to groundwater (Pant, 2018), and hospital wastewater treatment using hydrolytic bacteria
705 (Ethica et al., 2018).

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

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719 **4.3.4. Cluster 4: pharmaceutical waste**

720 From the waste management perspective, two main streams of pharmaceutical waste are
721 (1) pharmaceutical wastes produced by households and in primary care treatment facilities,
722 including unused, unwanted, or expired drugs or medicines with vials and syringes, and (2)
723 pharmaceutical wastes, including at least one type of medical waste, generated by pharmacies,
724 clinics, hospitals, and other healthcare and research facilities (Vallini and Townend, 2010;
725 Voudrias et al., 2012). Environmental contamination in the wake of active ingredients in
726 pharmaceutical waste has become an emerging global concern (Chung and Brooks, 2019) for the

727 environment and eco-system, which calls for more preventive actions and inclusive environmental
728 stewardship of pharmaceuticals.

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

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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

773 towards achieving sustainable HCW management (Parida et al., 2019). Woromogo et al. (2020)
774 showed that a good level of knowledge among medical staff more likely leads to favorable attitudes
775 towards HCW management. Besides, a good level of both knowledge and attitudes positively
776 affects the associated HCW management practices, indicating the important role of knowledge and
777 attitudes in successfully adopting HCW management policies and strategies. However, Mannocci
778 et al. (2020) outlined the need for cross-sectional studies to develop a standardized and
779 methodologically validated tool to assess the knowledge, attitude, and practices of healthcare
780 professionals to better manage HCW activities. Due to the differences in national legislation, the
781 healthcare industry settings, education systems, and cultural contexts, assessing the level of
782 knowledge, attitudes, and practices regarding HCW management seems challenging and needs
783 specific customizations on predesigned questionnaires.

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

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

792 In particular, based on the results provided in previous sections, potential research avenues for
793 further research in the future regarding HCW management towards implementing a CE are
794 presented in this section and summarized in Figure 7. Overall, three lines of research were

795 identified to support the CE transition in the healthcare industry and HCW management context
796 as follows:

797 • **Effective pharmaceutical waste management**

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

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

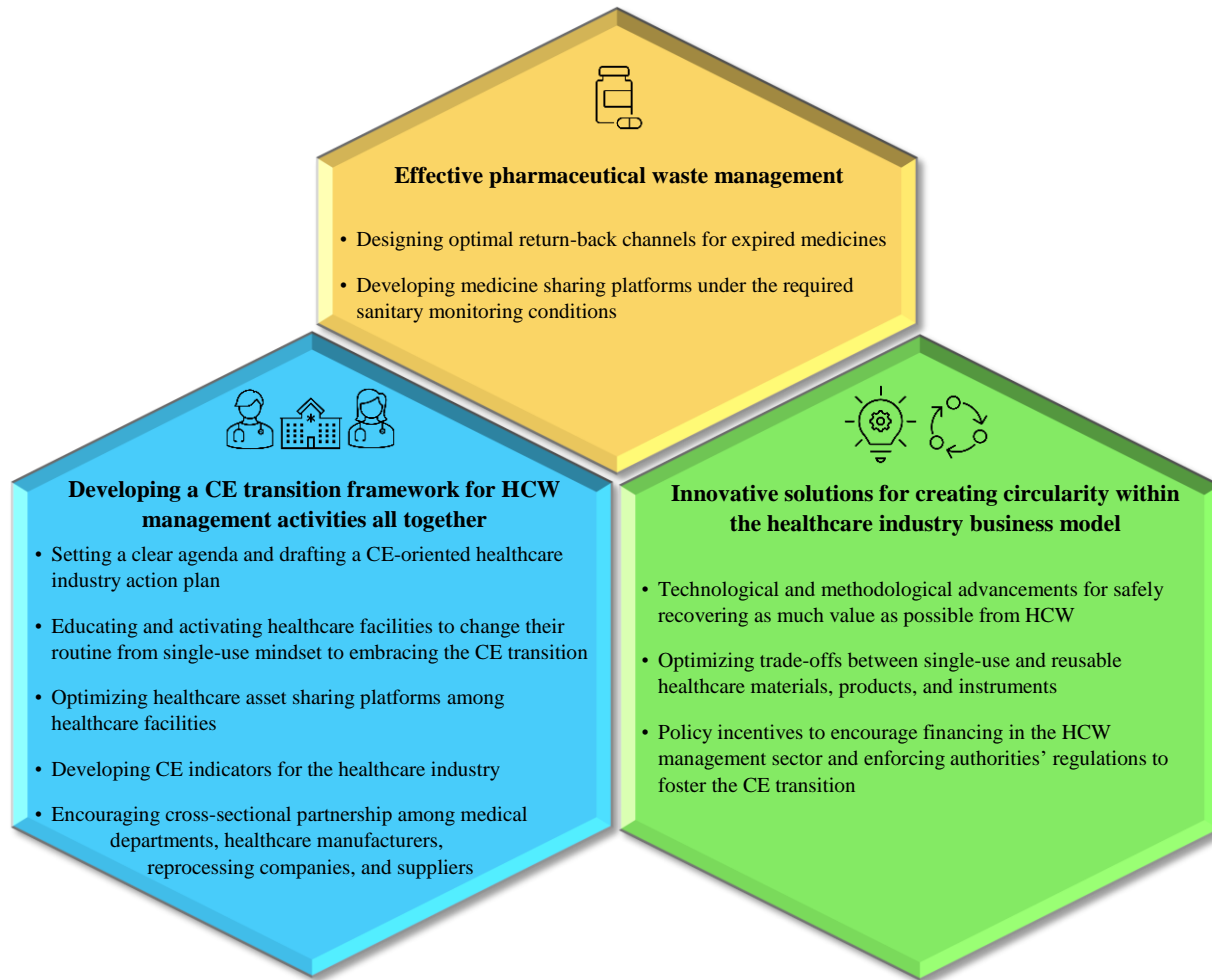
813 A few pieces of research regarding the adoption of a CE perspective for healthcare
814 organizations have been conducted recently. For instance, Voudrias (2018) highlighted some steps
815 that should be taken by healthcare facilities, including designing reusable items instead of single-
816 use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

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

833 • **Innovative solutions for creating circularity within the healthcare industry business**
834 **model**

835 The complex issue of reusing and reprocessing healthcare materials, products, and instruments
836 has been discussed in the waste management debate over recent years. On the one hand, disposable
837 and single-use materials and products are widely used to control infection in the healthcare
838 industry, increasing HCW generation. Replacing single-use products with reusable ones can
839 significantly reduce the rate of HCW produced by healthcare facilities, particularly hospitals. For
840 instance, Kwakye et al. (2011) denoted that a 1000-bed hospital is estimated to reduce 15,500
841 waste kg/year and save 175,000 US\$/year only by using reusable sharp containers instead of

842 disposable ones. On the other hand, although reprocessing of single-use products by healthcare
843 facilities, which refers to reusing single-use products after repairing, cleaning, and sterilizing,
844 could save costs and reduce waste, it faces many challenges, such as ethical, legal, and patient
845 safety issues (Voudrias, 2018). The CE discourse in the healthcare industry is still in its infancy
846 stage and highly needs more innovative approaches towards creating circularity and closing the
847 loops in delivering high-quality healthcare services with fewer materials used and less HCW
848 produced. Therefore, investigating innovative solutions for creating circularity within the business
849 model and supply chain of the healthcare industry through policy incentives and technological
850 advancements is recommended as another potential future research avenue. In this vein, three
851 identified research areas to support the CE transition in the healthcare industry are: (1)
852 technological and methodological advancements for safely recovering as much value as possible
853 from HCW. Hence, various solutions should be developed and investigated at different scales to
854 ensure maximal energy recovery from HCW streams. These solutions should be thoroughly
855 scrutinized using advanced sustainability assessment tools, which have been effectively employed
856 in various sectors of the waste management and valorization domain, such as life cycle assessment
857 (Khoshnevisan et al., 2020; Rajaeifar et al., 2017), exergy analysis (Barati et al., 2017; Tabatabaei
858 et al., 2021), exergoeconomic analysis (Aghbashlo et al., 2019b; Soltanian et al., 2019), and
859 exergoenvironmental analysis (Aghbashlo et al., 2019a, 2018); (2) optimizing trade-offs between
860 single-use and reusable healthcare materials, products, and instruments to replace as much single-
861 use as possible with reusable ones to close the supply chain loops and maximize the healthcare
862 resource efficiency; and (3) policy incentives to encourage financing in the HCW management
863 sector and enforcing authorities' regulations to foster the CE transition, in particular within the
864 context of developing countries.



865

866 **Fig. 7.** Future research directions towards implementing a circular economy (CE) in the healthcare industry and
 867 healthcare waste (HCW) management.
 868

869 **6. Concluding remarks**

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

876 research on sustainable HCW management towards implementing a CE within the healthcare
877 industry.

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

894 The theoretical/practical implications of this inclusive review for researchers, practitioners,
895 and policy-makers involved in the healthcare industry and HCW management practices are
896 outlined herein. Researchers and scholars are served by (i) rendering a comprehensive image of
897 HCW management developments over time, (ii) identifying the most influential articles and
898 journals that mainly have directed this field of study, (iii) mapping collaboration networks of

899 contributing countries, institutions, and funding agencies, (iv) providing hotspots in the HCW
900 management through employing keyword-based analyses, (v) unfolding prominent research
901 themes and subject areas which have shaped the main body of knowledge in HCW management,
902 and (vi) drafting a research agenda for the healthcare industry and accordingly HCW management
903 in line with CE principles. For practitioners, policy-makers, and official authorities, the findings
904 of the present study can be used as a guideline to (i) increase the understanding of different HCW
905 management practices, from waste identification and prediction to waste disposal and incineration,
906 and their impacts on the environment, human health, and workers safety, (ii) support implementing
907 effective HCW management practices according to CE principles towards a cleaner and
908 sustainable environment.

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

917

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