Waste management beyond the COVID-19 pandemic: Bibliometric and text mining analyses

Waste management beyond the COVID-19 pandemic: Bibliometric and text mining analyses

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Abstract

The outbreak of the COVID-19 pandemic has significantly increased the demand for personal protective equipment, in particular face masks, thus leading to a huge amount of healthcare waste generated worldwide. Consequently, such an unprecedented amount of newly emerged waste has posed significant challenges to practitioners, policy-makers, and municipal authorities involved in waste management (WM) systems. This research aims at mapping the COVID-19-related

scientific production to date in the field of WM. In this vein, the performance indicators of the target literature were identified and discussed through conducting a bibliometric analysis. Such conceptual structure of COVID-19-related WM research, including seven main research themes, were uncovered and visualized through a text mining analysis as follows: (1) household and food waste, (2) personnel safety and training for waste handling, (3) sustainability and circular economy, (4) personal protective equipment and plastic waste, (5) healthcare waste management practices, (6) wastewater management, and (7) COVID-19 transmission through infectious waste. Finally, a research agenda for WM practices and activities in the post-COVID-19 era is proposed, focusing on the following three identified research gaps: (i) developing a systemic framework to properly manage the pandemic crisis implications for WM practices as a whole, following a system thinking approach, (ii) building a circular economy model encompassing all activities from the design stage to the implementation stage, and (iii) proposing incentives to effectively involve informal sectors and local capacity in decentralizing municipal waste management, with a specific focus on developing and less-developed countries.

Keywords: COVID-19, Plastic waste, Healthcare waste, Municipal solid waste, Wastewater, Personal protective equipment.

1. Introduction

The novel coronavirus-caused infectious disease 2019 (COVID-19) pandemic, as the most drastic health calamity of this century (Chakraborty and Maity, 2020), has severely impacted the economic, social, and environmental aspects of the global community and human well-being (Ranjbari et al., 2021c). Disruptions in economic activities and commodity markets (Rajput et al., 2021), limitations in mobility and industrial activities but at the same time, improving the air

quality of the cities (Ambade et al., 2021; Gautam et al., 2021; Gautam, 2020; Ravina et al., 2021), and challenges in implementing the 2030 Agenda for Sustainable Development (Bherwani et al., 2021; Ranjbari et al., 2021b) are only a few instances of the pandemic's implications for the global community. This pandemic through posing a significant increase in healthcare waste generation, which is an important transmission medium for the virus, has led to creating critical challenges for waste management (WM) practices globally (C. Chen et al., 2021; Gautam et al., 2022). The dramatic increase of personal protective equipment waste often ends up being treated by traditional disposal methods that have gravely pressured incineration and landfill facilities (Wang et al., 2021). In this vein, the waste generated in the wake of COVID-19, such as masks, gloves, sanitary papers, and clothing materials needs to be considered as medical waste, highlighting the importance of safely handling at the household level, and properly treatments at the municipal level (Musa et al., 2020).

However, there are still many uncertainties regarding the effects of the pandemic outbreak on various waste streams generated from a macro lens. On one hand, COVID-19 restrictions and partial lockdowns imposed by governments have decreased some industrial and business activities, which usually generate large amounts of waste (Naughton, 2020). On the other hand, in addition to increased medical waste, some waste streams such as agricultural waste or household wastes may increase due to the high demand for home delivery as well as increasing home cooking in the wake of the pandemic (Dente and Hashimoto, 2020). Consequently, a system thinking approach (Ranjbari et al., 2019; Shams Esfandabadi et al., 2020), as well as more reliable real-time WM data is needed to truly map changes in waste generation in the post-COVID-19 era (Naughton, 2020).

As a response to the urgent call for action against adverse effects of the pandemic, many COVID-related studies have been conducted within various domains and disciplines. In this regard, a massive amount of research has also been conducted focusing on the effects of the pandemic on WM systems, practices, and different waste streams, such as healthcare WM challenges (de Aguiar Hugo and Lima, 2021), household food waste (Amicarelli and Bux, 2021; Vittuari et al., 2021), effective plastic WM during and post pandemic (Vanapalli et al., 2021), solid waste and environmental impacts (Urban and Nakada, 2021), municipal waste disposal behavior (Vu et al., 2021), face mask waste generation (Torres and De-la-Torre, 2021), reusing COVID-19 face mask as a novel solution to the emerging COVID-19 waste issue (Rehman and Khalid, 2021), solid waste generation and management strategies (Liang et al., 2021), single-use plastic waste (Leal Filho et al., 2021), behavioral impacts on residential food provisioning, use, and waste (Babbitt et al., 2021a), perceptions of people towards household waste management in the wake of the pandemic (Acharya et al., 2021), municipal solid waste management (Yousefi et al., 2021), waste production in households (Filho et al., 2021), and enabling circular economy model in solid waste management as a recovery plan post COVID-19 (Sharma et al., 2021).

The increasing interest of researchers and academic communities in contributing to COVID-related WM practices has led to fragmented literature in this domain. As a result, an inclusive landscape of the pandemic challenges for WM is still lacking in the literature. To the best of the authors' knowledge, so far, no research has conducted a comprehensive bibliometric review on the pandemic implications for WM practices. Therefore, to fill this gap, this research aims at providing a comprehensive review of the COVID-related scientific production to date in the WM field. On this basis, bibliometric and text mining analyses are conducted to address the following research questions:

RQ1. How has the field of research regarding WM in the context of COVID-19 performed?

RQ2. What are the main research themes of WM in the COVID-19-related scientific production?

RQ3. What are the potential research gaps and future directions for WM in the post-COVID-19 era?

The remainder of this research is structured as follows. The methodology is described in Section 2. The bibliometric results, including the performance analysis and science mapping of the WM in the pandemic context, are presented and discussed in Section 3. Section 4 provides the research gaps and future research directions to further develop WM practices considering COVID-19 implications. And finally, Section 5 concludes the main findings and presents the limitations of the current research.

2. Research design and methodology

In this research, an analytical method combining bibliometric and text mining analyses adopted from Ranjbari et al. (Ranjbari et al., 2022, 2021a) was applied to answer the research questions. In this regard, the bibliometric analysis was used to evaluate and map the performance of WM research taking COVID-19 implications into account, corresponding to the first research question. As a part of the bibliometric analysis, bibliographic coupling was conducted, which aggregates articles in different clusters based on the cited references they have in common in their bibliographies. Therefore, the formed clusters in bibliographic coupling are made of the sample articles available in our dataset. On the other hand, a text mining analysis was conducted to discover the main research themes and trends of the WM literature in the context of the pandemic, corresponding to the second research question. The text mining analysis was conducted on the

titles and abstracts of the articles within our dataset to extract the noun phrases used by the authors. These phrases are then clustered based on their co-occurrence links (Waltman et al., 2010) to form the main research themes within the studied field of research. Hence, the clusters built in this analysis contain the frequent noun phrases applied in the titles and abstracts of the sample articles in our dataset. Finally, according to the insights provided by the bibliometric and text mining analyses, research gaps and potential avenues for future studies are presented, corresponding to the third research question.

Fig. 1 illustrates the main structure of this research approaching the research questions.

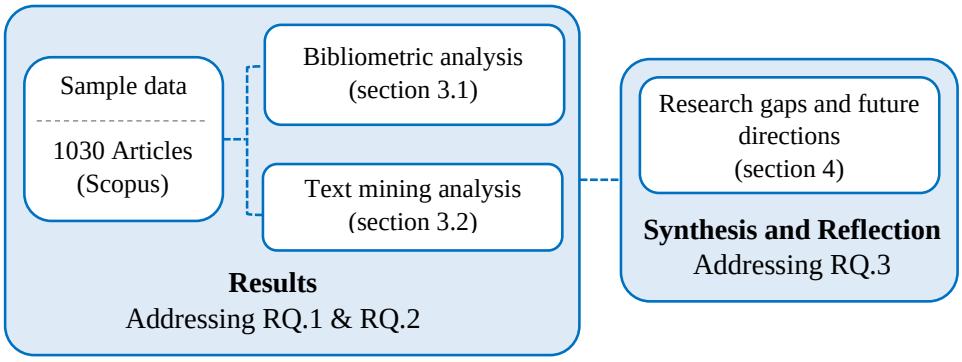

Fig. 1. The research framework design

2.1. Search string and data collection

In order to extract as many relevant studies as possible from the target literature, using a well-structured research protocol has been widely highlighted in the literature as one of the most important prerequisites in conducting systematic reviews (Chaudhary et al., 2021; Makrides et al., 2021; Zahedi et al., 2016). On this basis, a structured search string was formulated using different

127 combinations of the keywords "COVID-19" and "waste" as the main two concepts which shape
128 the present review. Consequently, the following search string was constructed to collect articles
129 from the Scopus database: ("COVID-19" OR "pandemic" OR "Coronavirus" OR "SARS-CoV-2")
130 AND "waste".

131 Since this research aims to map all waste streams considering the pandemic effects, we decided
132 not to limit the keyword "waste" with different waste streams, such as municipal solid waste,
133 medical waste, healthcare waste, or plastic waste to cover WM practices for various waste streams
134 as much as possible. The initial run of the search string on the titles and abstracts of articles in the
135 Scopus database returned a total of 1567 articles. Due to the recentness of the COVID-19
136 pandemic, the results were limited to the articles published in 2020 and 2021. Moreover, to ensure
137 the reliability of the sample data, only peer-reviewed journal articles were included in the research
138 leading to excluding other types of documents, such as conference proceedings, book chapters,
139 and editorial notes from the study. Besides, non-English materials were excluded from the
140 remained articles. As a result, a final sample of 1030 articles was selected as the main data for
141 conducting the bibliometric and text mining analyses. Table 1 summarizes the steps taken in this
142 research to construct the final sample.

143 **Table 1.** Steps of the data collection process.

Search string	"COVID-19" OR "pandemic" OR "Coronavirus" OR "SARS-CoV-2" **AND** "Waste"
Fields mined	Article titles, abstracts, author keywords, and keywords plus

Database	Scopus
Initial Result	1567 articles
Search date	August 8, 2021
Inclusion criteria	Only peer-reviewed journal articles, only English materials, limited to 2020-2021
Final sample	1030 articles

2.2. Data analysis

The bibliometric analysis, as a statistical tool to evaluate the performance of an extensive amount of scientific production, has been broadly used for science mapping in recent years. This is due to the capability of the bibliometric analysis in drawing conclusions about the links among articles, journals, authors, keywords, citations, and co-citations networks (Feng et al., 2017), which supports researchers in discovering research themes and trends, and future research directions. In this research, the VOSviewer software version 1.6.16 developed by van Eck and Waltman (2010) was employed to run the bibliometric analysis. Accordingly, the performance of WM research within the COVID-related scientific production was investigated and mapped by presenting bibliometric performance indicators focusing on (i) geographical distribution of publications, (ii) authors' productivity and influence, (iii) core journals, (iv) articles, and (v) keyword-based analysis to unfold research tendencies and hotspots. In this regard, data cleaning, as an essential step in keyword-based analyses to reduce the presence of redundant and useless data (Bresciani et al., 2021; Ranjbari et al., 2020), was performed in a reasonable manner, for instance by (i) unification of the English writing styles, (ii) merging singular and plural as well as full and short

forms of the keywords, (iii) excluding general keywords without conveying any specific meaning, such as review or article. Besides, all forms of referring to the COVID-19 pandemic, including Coronavirus, pandemic, and SARS-COV-2 were transformed into “COVID-19" to more accurately assess the occurrence of this keywords.

In addition to the provided bibliometric indicators, a text mining analysis based on a term co-occurrence algorithm (Van Eck and Waltman, 2011) using the text mining module of VOSviewer version 1.6.16 was also conducted on the manuscripts’ titles and abstracts (1030 articles) included in the final sample. As a result, semantic structures and phrase patterns that constructed the main research themes of WM studies post COVID-19 were identified and visualized. A data cleaning step was also taken before text mining analysis by (i) unification of the English writing styles, and (ii) merging full and short forms of the keywords.

3. Results and discussion

In this section, the results of the bibliometric analysis and text mining analysis are presented to address the first and second research questions, respectively.

3.1. Bibliometric results: performance indicators

3.1.1. Geographical distribution of publications

The spatial and geographic distribution of articles provides insight into the main active countries in terms of publication within the waste context in the COVID-19 era. A total of 91 countries have published articles within our studied field and 82 of these countries are a part of a co-authorship network. Fig. 2 illustrates the countries’ co-authorship network of the WM research post-

pandemic, consisting of nodes with different sizes corresponding to the number of articles published by a country, and links with different thicknesses corresponding to the strength of the co-authorship between each pair of countries. Table 2 provides the list of the top 10 countries in terms of the number of published articles, number of collaborating countries (number of links), total number of articles co-authored (total link strength), and the number of cites to their articles.

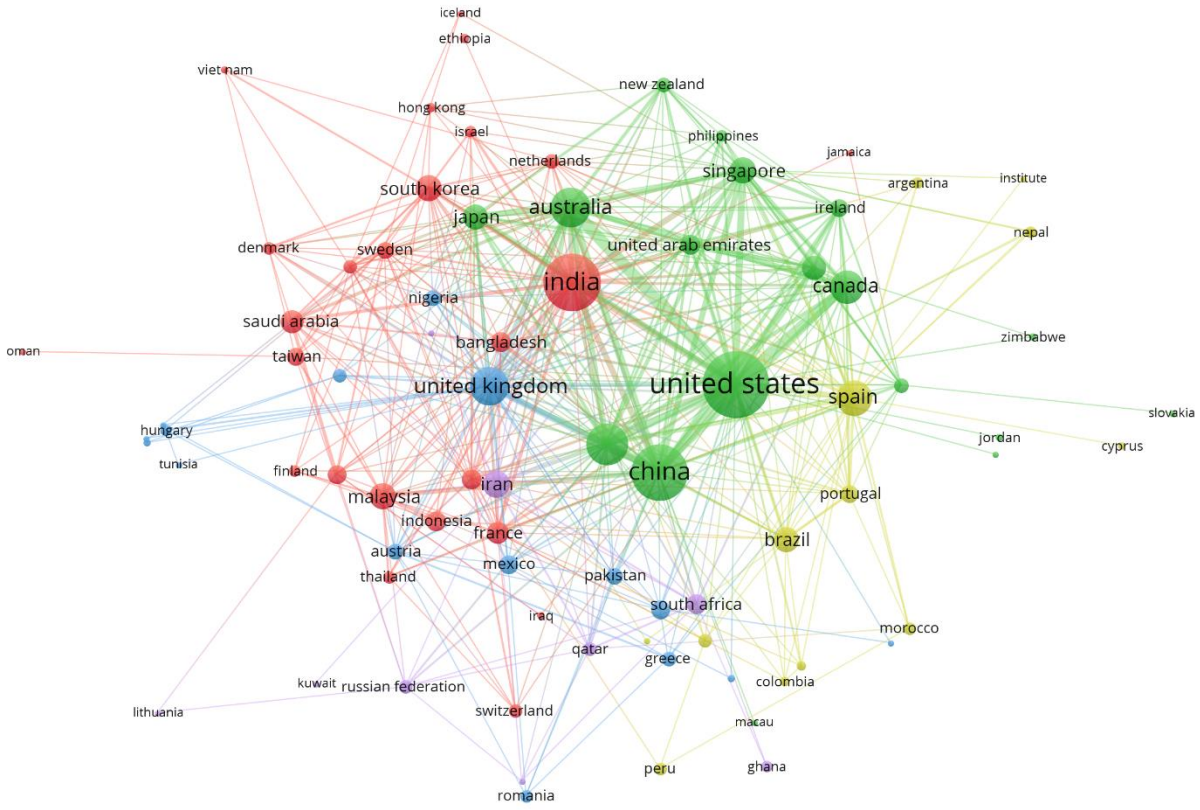

Fig. 2. The countries' co-authorship network of WM research post-COVID19 pandemic

Table 2. Top 10 countries in terms of the number of published articles, number of co-author countries, total number of co-authorship, and the number of cites to their articles

Rank	Published articles	Number of collaborating countries	Total number of documents co-authored	Citations
1	USA (137)	USA (49)	USA (169)	USA (2080)
2	India (101)	UK (42)	China (132)	Australia (1197)
3	China (98)	China, India (39)	Australia (120)	Japan (1036)
4	Italy (55)	Italy (37)	Italy (108)	Italy (988)
5	Australia (48)	Australia (34)	India (105)	China (840)
6	UK (47)	Singapore (29)	UK (94)	India (754)
7	Spain (39)	Spain (28)	Singapore (84)	Spain (486)
8	Canada (34)	Japan (26)	Canada (72)	UK (448)
9	Iran (23)	South Korea (25)	Spain (54)	Mexico (423)
10	Malaysia (22)	Poland, United Arab Emirates (23)	Japan (53)	Ecuador (357)

As can be seen in Table 2, the USA with 137 articles, 49 collaboration links, 169 co-authorships, and 2080 citations is ranked first in all four rankings. Although the second and third ranks in these rankings address different countries, Italy is ranked fourth with 55 articles, 37 co-author countries, 108 collaborations, and 988 earned citations. UK, China, Australia, India, and Spain also appear among the top 10 countries in all the four lists, but their position differs in each ranking. As the strength of the links in Fig. 2 shows, most of the collaboration of the USA in their publications have taken place with Australia (21 co-authorship), Canada (16 co-authorship), and China (15 co-

198 authorship), which are also the strongest links in this network. The next strong collaboration refers
199 to the co-authorship of Italy with China and the USA, each happening 12 times.

200 ### 3.1.2. Authors productivity and influence

201 Research authors play a key role in the evaluation of the development in an academic field (Guo
202 et al., 2021). A total of 3,348 authors contributed to the research in the field of WM considering
203 the challenges caused by COVID-19, among whom 80 authors have contributed at least in 3
204 articles. Table 3 and Table 4 provide the list of authors with the highest number of articles (most
205 productive authors) and the highest number of citations (most influential authors) in our dataset,
206 respectively, and also the number of their co-authors and co-authorship. Based on the lists provided
207 in these tables, M. Kitajima is the most productive and most influential author among the 3348
208 authors in our dataset.

209 **Table 3**. The most productive authors in WM research post-COVID-19 pandemic

Author	Articles	Citations	Co-authors	Total co-authorship
Kitajima M.	8	848	19	43
Li J.	8	490	22	24
Chen X.	7	24	17	17
Liu Y.	7	72	18	19
Bibby K.	6	714	16	48
Wang J.	6	60	6	9
Wang Y.	6	7	8	8
Zhang L.	6	37	12	16

Ahmed W.	5	713	16	48
Bivins A.	5	538	16	45
Lee J.	5	11	1	1
Li X.	5	18	5	5
Zhang J.	5	132	8	11
Zhang X.	5	103	8	9
Zhang Y.	5	57	6	6

210

211 **Table 4.** The most influential authors in WM research post COVID-19 pandemic

Author	**Citations**	**Articles**	**Co-authors**	**Total co-authorship**
Kitajima M.	848	8	19	43
Bibby K.	714	6	16	48
Ahmed W.	713	5	16	48
Bivins A.	538	5	16	45
Mueller J.F.	538	4	15	44
Simpson S.L.	538	4	15	44
Thomas K.V.	538	4	15	44
Verhagen R.	538	4	15	44
Smith W.J.M.	521	3	15	35
Li J.	490	8	22	24

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3.1.3. Core journals

The 1030 available articles in the WM field of research post COVID-19 within our dataset have been published in 351 journals. Out of this pool of journals, 35 have published at least 3 of the articles in the dataset. Fig. 3 and Fig. 4 focus on the journal publications and show the top ones based on the number of published articles and the number of citations to their articles, respectively. As can be seen in these figures, *Science of the Total Environment* has both the largest share of published articles and the highest number of citations to its articles. Besides, there is a significant gap between this journal and the second-ranked journals both in terms of productivity and influence. In fact, while *Science of the Total Environment* has published 90 articles, *Sustainability* as the next productive journal has published 17 articles, followed by *Resource, Conservation and Recycling* that has 13 articles in our database. Moreover, in terms of the citations earned by the published articles, *Science of the Total Environment* is followed by *Water Research* and *Resource, Conservation and Recycling*, with 426 and 297 citations, respectively, which are far away from the 2759 cites received by *Science of the Total Environment*. Therefore, *Science of the Total Environment* can be regarded as the leading journal in the field of WM post COVID-19 from this lens of analysis.

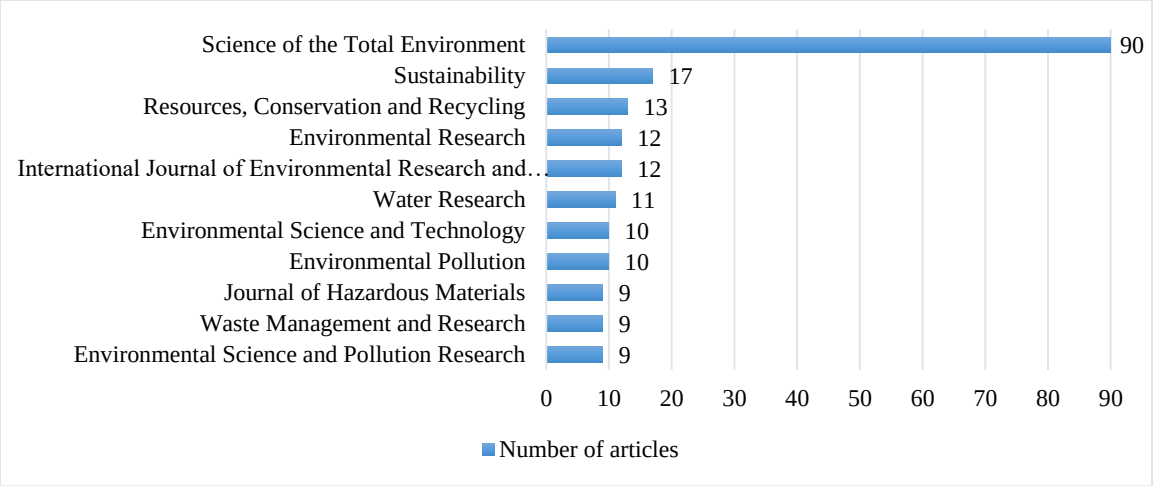


Fig. 3. Top productive journals in terms of published articles

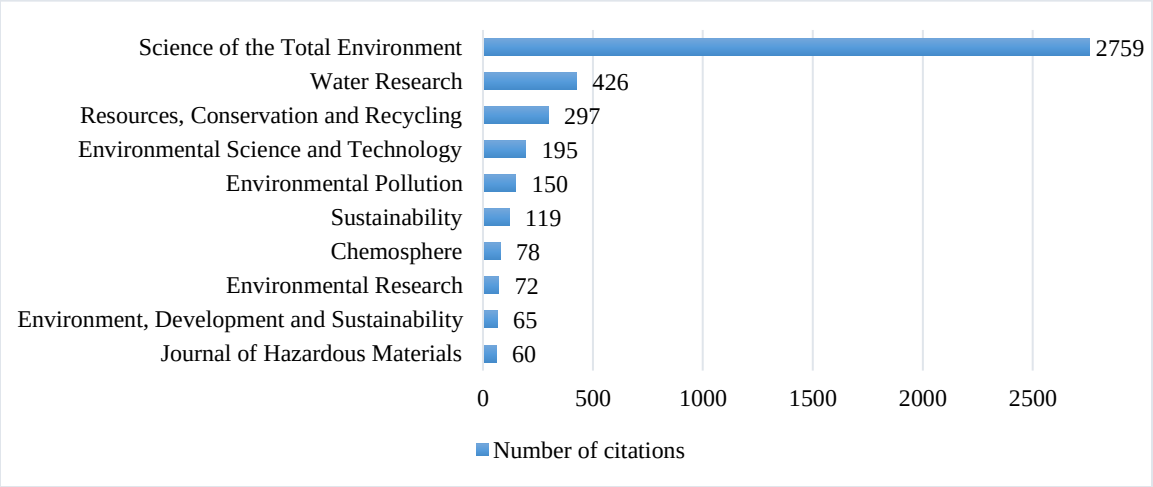


Fig. 4. Top influential journals in terms of the number of citations to their articles

3.1.4. Articles

In this section, two main analyses are conducted on the articles concerning the citations received by the articles and their bibliographic coupling.

3.1.4.1. Influential articles

One of the ways to evaluate the influence of an article on a related research area is to consider the number of times it is cited (Merigó et al., 2015). Therefore, Table 5 presents the list of the top 10 most cited articles within the WM filed post COVID-19. As shown in this table, two papers share the eighth position by attracting 123 citations. The most influential article in Table 5 with 394 citations is a research conducted by Ahmed et al. (2020a) that has focused on the first detection of the COVID-19 virus in untreated wastewater in Australia. Similarly, the first detection of SARS-CoV-2 RNA in wastewater has been considered in Italy (La Rosa et al., 2020) and Japan (Haramoto et al., 2020) in the fifth and eighth most influential articles with 193 and 123 citations, respectively. The existence of SARS-CoV-2 RNA in wastewater treatment plants in Spain and the USA was investigated by Randazzo et al. (2020) and Wu et al. (2020) in the third and tenth influential articles with 274 and 101 citations, respectively. Besides, wastewater-based epidemiology is addressed by Hart and Halden (2020) in the seventh-ranked paper, and a review of the methodologies for the detection and quantification of SARS-CoV-2 in wastewater and the potential of wastewater surveillance regarding the pandemic is presented by Kitajima et al. (2020) in the sixth influential article. Fadare and Okoffo (2020) and Prata et al. (2020) address plastic waste in their research, and finally, Zambrano-Monserrate et al. (2020) and Saadat et al. (2020) analyze the environmental effects of the pandemic, as the eighth, ninth, second and fourth highly cited articles within the studied research area, respectively.

Furthermore, considering the journals containing the most influential articles in Table 5, out of the 11 available articles, 7 have been published in *Science of the Total Environment*, which was

introduced as the most productive and influential journal in the context of WM post pandemic in section 3.1.3.

Table 5. Top 10 highly cited articles in the WM research within the COVID19 area

Rank	Author	Title	Journal	Citation
1	Ahmed et al. (2020a)	First confirmed detection of SARS-COV-2 in untreated wastewater in Australia: a proof of concept for the wastewater surveillance of COVID-19 in the community	Environmental Science & Technology Letters	394
2	Zambrano-Monserrate et al. (2020)	Indirect effects of COVID-19 on the environment	Science of The Total Environment	356
3	Randazzo et al. (2020)	SARS-CoV-2 RNA in wastewater anticipated COVID-19 occurrence in a low prevalence area	Water Research	274
4	Saadat et al. (2020)	Environmental perspective of COVID-19	Science of The Total Environment	201
5	La Rosa et al. (2020)	First detection of SARS-CoV-2 in untreated wastewaters in Italy	Science of The Total Environment	193

6	Kitajima et al. (2020)	SARS-CoV-2 in wastewater: State of the knowledge and research needs	Science of The Total Environment	175
7	Hart and Halden (2020)	Computational analysis of SARS-CoV-2/COVID-19 surveillance by wastewater-based epidemiology locally and globally: feasibility, economy, opportunities and challenges	Science of The Total Environment	140
8	Haramoto et al. (2020)	First environmental surveillance for the presence of SARS-CoV-2 RNA in wastewater and river water in Japan	Science of The Total Environment	123
	Fadare and Okoffo (2020)	COVID-19 face masks: A potential source of microplastic fibers in the environment	Science of The Total Environment	123
9	Prata et al. (2020)	COVID-19 Pandemic Repercussions on the Use and Management of Plastics	Environmental Science & Technology	113
10	Wu et al. (2020)	SARS-CoV-2 titers in wastewater are higher than expected from clinically confirmed cases	mSystems	101

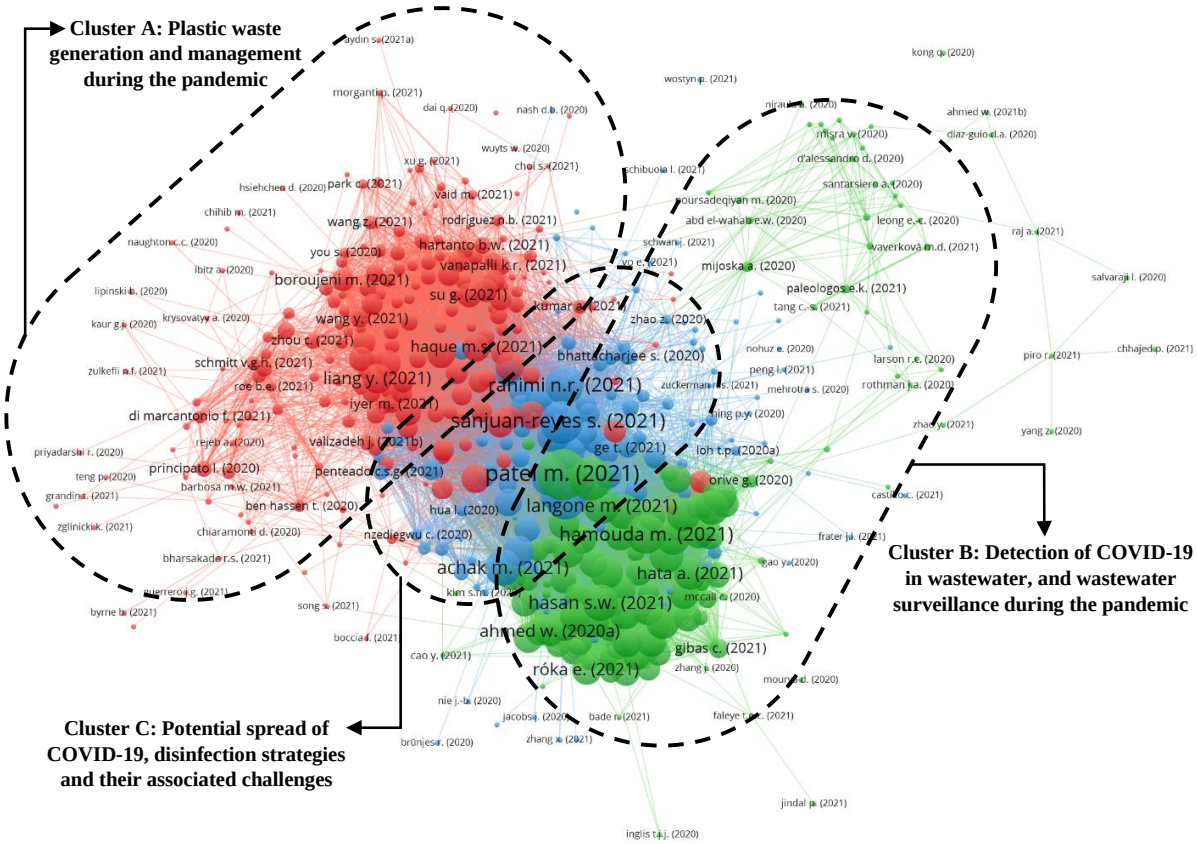
3.1.4.2. Bibliographic coupling of articles

In order to put the articles in relevant categories and show the main themes of the WM research in the COVID-19 era, bibliometric coupling of the articles was conducted based on the references that they share. Out of the 1030 research and review articles in our dataset, only 658 documents had at least one common reference with other documents. Therefore, these 658 articles were considered for the bibliographic coupling in this section. Fig. 5 visualizes the articles grouped in three specific clusters. Each cluster is addressed by a different color and is named based on the main sense of the articles located in it. The size of the bubbles points to the number of citations of the corresponding article and the link between each pair of articles shows their co-occurrence. The top 10 highly cited articles of each category are listed in Table 6.

The focus of the majority of the papers in research category A (red color in Fig. 5) is on the generation of plastic waste linked with the usage of face masks (Das et al., 2020; Fadare and Okoffo, 2020) and other personal protective equipment during the pandemic, as well as related management of the generated waste (Prata et al., 2020; Sharma et al., 2020; Vanapalli et al., 2021). This category is supported by articles that share similar references with the plastic waste research but target the management of pandemic-related waste (Ibn-Mohammed et al., 2021; Peng et al., 2020). The unsustainable use of single-use plastics to protect people against the pandemic has exposed ecosystems to several environmental threats by producing a huge amount of plastic pollution (Sarkodie and Owusu, 2021). On one hand, the increase in waste generated, and on the other hand, the reduction in the recycling of used materials have posed serious challenges to water, land, and air (Zambrano-Monserrate et al., 2020). In this regard, the global unprecedented rise of using billions of face masks to slow down the COVID-19 transmission rate has been under intense

283 debate as a critical environmental issue (Fadare and Okoffo, 2020). Replacing common face
284 masks, which are produced from petrochemicals derived raw materials, with degradable bio-based
285 face masks using raw materials that are side-stream products of local industries was proposed by
286 Das et al. (2020) as a sustainable solution for the pandemic WM.

287 Detection of SARS-COV-2 RNA in wastewater (Ahmed et al., 2020a; La Rosa et al., 2021; Orive
288 et al., 2020) is the focal point of research category B, which is shown in green in Fig. 5. This
289 category also includes research on wastewater surveillance post COVID-19 (Daughton, 2020),
290 which highlights the important role of wastewater-based epidemiology as an effective tool to
291 manage the pandemic (Ahmed et al., 2020b) and minimize domino effects of COVID-19
292 restrictions that stress humans and economies (Daughton, 2020). Besides, since wastewater is
293 relatively affordable and can be easily collected and monitored at different population aggregation
294 levels, wastewater surveillance in the COVID-19 outbreak can provide a real-time and cost-
295 effective health assessment rather than case reporting (Thompson et al., 2020). The top 6 papers
296 in this category have been previously reported among the most influential articles in section
297 3.1.4.1. Finally, research category C (blue color in Fig. 5) stands mainly based on the research
298 articles addressing the potential spread of the SARS-COV-2 virus through solid waste (Nzediegwu
299 and Chang, 2020), wastewater (Zhang et al., 2020), environmental matrices and surfaces
300 (Carraturo et al., 2020; Mouchtouri et al., 2020), and water (Carducci et al., 2020), and is supported
301 by research articles addressing preventive measures (Wang et al., 2020) and disinfection strategies
302 (Ilyas et al., 2020).



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304 **Fig. 5.** Bibliographic coupling of the articles within the field of WM research post-COVID19 pandemic

305 **Table 6.** Highly cited articles within the main identified research categories.

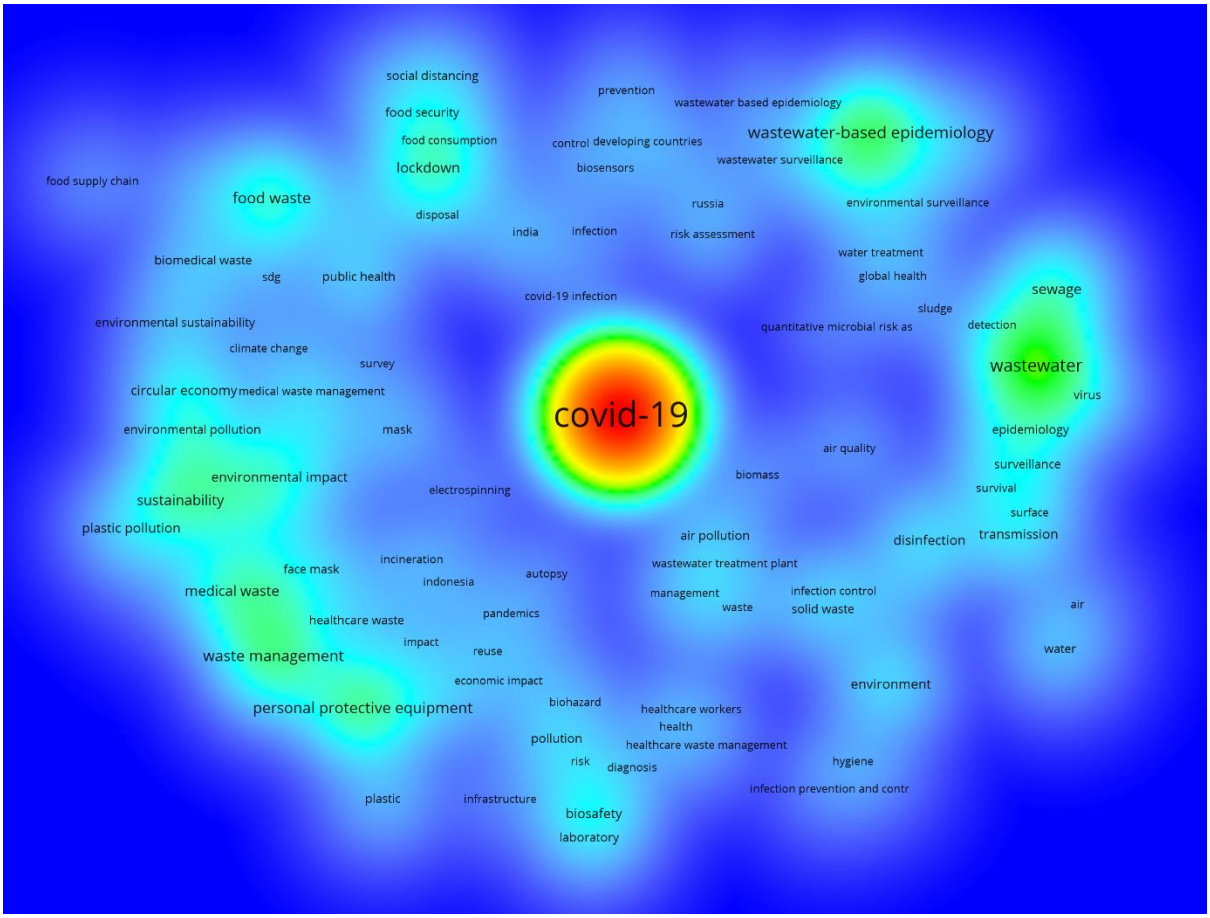
Research category A: Plastic waste generation and management during the pandemic		**Research category B:** Detection of COVID-19 in wastewater, and wastewater surveillance during the pandemic		**Research category C:** Potential spread of COVID-19, disinfection strategies and their associated challenges	
Reference	**Article citation**	**Reference**	**Article citation**	**Reference**	**Article citation**

Zambrano-Monserrate et al. (2020)	356	Ahmed et al. (2020a)	394	Saadat et al. (2020)	201
Fadare and Okoffo (2020)	123	Randazzo et al. (2020)	274	Peccia et al. (2020)	93
Prata et al. (2020)	113	La Rosa et al. (2020)	193	Nzediegwu and Chang (2020)	65
Sharma et al. (2020)	82	Hart and Halden (2020)	140	Zhang et al. (2020)	63
Vanapalli et al. (2021)	65	Haramoto et al. (2020)	123	Carducci et al. (2020)	62
Mofijur et al. (2021)	53	Wu et al. (2020)	101	Carraturo et al. (2020)	61
Ibn-Mohammed et al. (2021)	52	Ahmed et al. (2020b)	100	Ilyas et al. (2020)	46
Ben Hassen et al. (2020)	42	Daughton (2020)	67	Wang et al. (2020)	38
Das et al. (2020)	38	La Rosa et al. (2021)	66	Lacy et al. (2020)	35
Peng et al. (2020)	33	Orive et al. (2020)	66	Ma et al. (2020)	33

306

3.1.5. Keyword analysis: research tendencies and hotspots

The analysis of keywords frequency provides a ground for the description of the research domain and the concentration of the collected articles. After cleaning the keywords data, 1765 unique keywords were identified, 119 of which had at least 3 occurrences. Then a heat map was developed for these 119 keywords based on their frequencies in VOSviewer, as illustrated in Fig. 6. As expected, COVID-19 (representing all forms of referring to the current pandemic) is the most frequent keyword, as pictured in Fig. 6, and the next main hot spots refer to wastewater, wastewater-based epidemiology, and personal protective equipment, which are in line with the research categories identified in the analysis of bibliographic coupling in section 3.1.4.2. To facilitate the identification of the most frequent keywords, the author keywords with the occurrence of more than 10 are reported in Table 7.



318

319 **Fig. 6.** The density visualization map of author keywords within the articles in the domain of WM post

320 COVID-19

321

322 **Table 7**. The most frequent author keywords in the domain of WM post COVID-19

Rank	Keyword	Frequency	Rank	Keyword	Frequency
1	COVID-19	422	12	Circular economy	13
2	Wastewater	47		Environment	13

3	Wastewater-based epidemiology	36	13	Disinfection	12
4	Personal protective equipment	30	14	Environmental impact	11
5	WM	28		Plastic pollution	11
6	Food waste	23		Transmission	11
7	Sewage	22	15	Environmental pollution	10
8	Medical waste	20		Face mask	10
9	Sustainability	19		Public health	10
10	Lockdown	16		Virus	10
11	Biosafety	14			

Since the keyword COVID-19 has a significantly higher frequency (422 occurrences) in comparison with the second most frequent keyword (wastewater with 47 occurrences), it has a co-occurrence with many of the keywords. Based on Table 8, COVID-19 has a pivotal role and appeared alongside wastewater, wastewater-based epidemiology, and personal protective equipment in the author keywords list of 43, 31, and 24 articles, respectively. However, to provide a clearer picture of the most frequent pairs of keywords, without considering “COVID-19” keyword, the most frequent pairs of keywords ignoring “COVID-19” are provided in Table 9. Personal protective equipment and WM, and also wastewater and wastewater-based epidemiology, both are the most frequent pairs of keywords with 7 occurrences. Circular economy and sustainability, and virus and wastewater both are ranked as the second most frequent pairs each

appearing in 6 documents. The third rank goes to 4 pairs, including biosafety and laboratory, consumer behavior and food waste, sewage and wastewater, and wastewater and water, each with 5 occurrences.

Table 8. The most frequent pairs of author keywords considering COVID-19 as the pivotal keyword

Keyword 1	Keyword 2	Frequency
COVID-19	Wastewater	43
COVID-19	Wastewater-based epidemiology	31
COVID-19	Personal protective equipment	24
COVID-19	WM	22
COVID-19	Sewage	19
COVID-19	Food waste	15
COVID-19	Lockdown	15
COVID-19	Medical waste	15
COVID-19	Biosafety	14
COVID-19	Sustainability	13

Table 9. The most frequent pairs of author keywords excluding COVID-19 from the list of keywords

Keyword 1	Keyword 2	Frequency
Personal protective equipment	WM	7

Wastewater	Wastewater-based epidemiology	7
Circular economy	Sustainability	6
Virus	Wastewater	6
Biosafety	Laboratory	5
Consumer behavior	Food waste	5
Sewage	Wastewater	5
Wastewater	Water	5

341

342 ## 3.2. Text mining results: thematic conceptualization

343 The text mining analysis was conducted on the titles and abstracts of the 1030 collected peer-
344 reviewed journal articles of our sample to uncover hidden semantic structures and research themes.
345 After cleaning the data, 16,345 unique noun phrases were identified. In order to base the analysis
346 on the sufficiently frequent terms, a minimum of 5 occurrences was considered as a criterion for
347 the selection of phrases, leading to the selection of 853 noun phrases. Then, to remove the general
348 terms (e.g. article, research, etc.) and focus on the main topic of this research, the 60% most
349 relevant identified terms were considered in the analysis based on the statistical method applied in
350 the VOSviewer software (Van Eck and Waltman, 2011). The obtained list of 512 terms was then
351 checked manually to remove the remaining general terms, which do not point to a specific research
352 theme, such as COVID-19 pandemic, coronavirus-caused infectious disease, and Middle East
353 respiratory syndrome. As a result, 454 unique phrases remained, which were used to build clusters
354 based on the co-occurrence of the terms to reveal the research themes in the WM research post
355 COVID-19 era. The seven major themes identified include (1) household and food waste, (2)

personnel safety and training for waste handling, (3) sustainability and circular economy, (4) personal protective equipment and plastic waste, (5) healthcare waste management practices, (6) wastewater management, and (7) COVID-19 transmission through infectious waste. Fig. 7 presents the thematic structure of the COVID-related WM research. Similar to Fig. 6, the size of the circles and the links between them show the occurrence of identified terms and their co-occurrence, respectively.

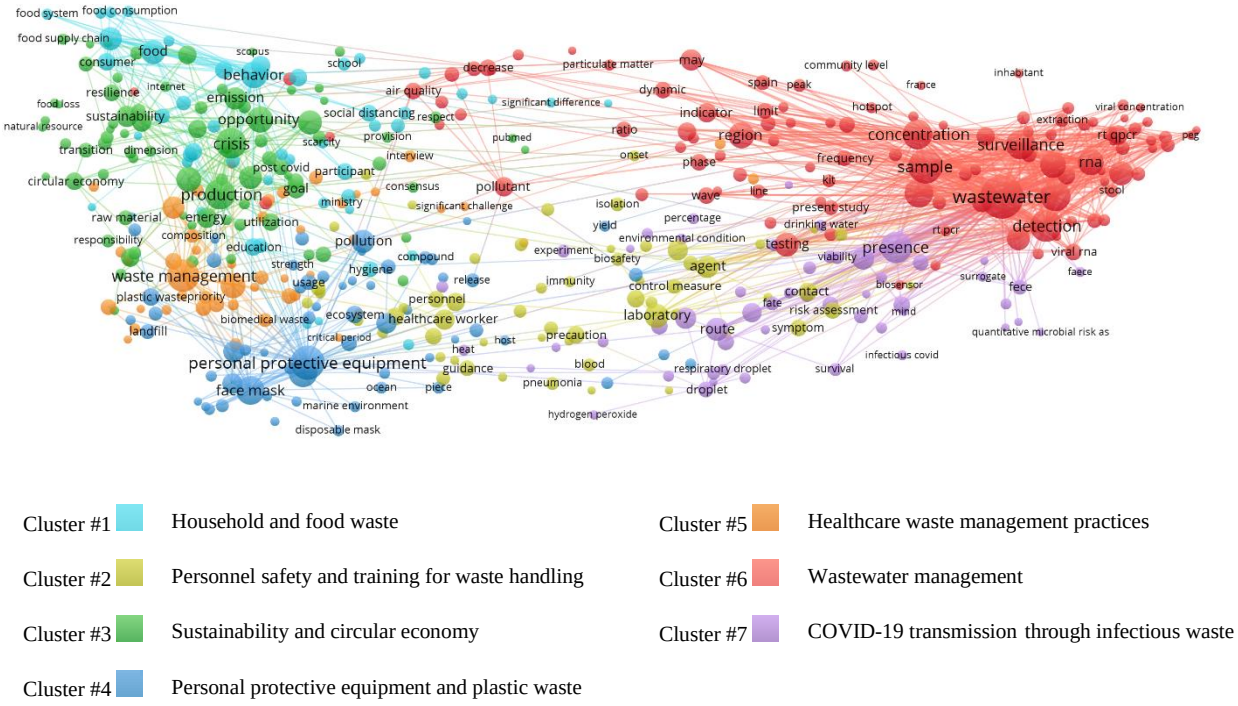


Fig. 7. Major research themes in COVID-related WM research

The first cluster refers to the household and food waste (cluster #1) considering the pandemic effects on the waste generated, consumer behavior and lifestyle, and food systems. The main terms in this research theme are behavior, food, food waste, consumer, household, food consumption, food system, lifestyle, sanitizer, and household waste. On this basis, the pandemic has highly impacted the food consumption and purchasing habits of people (Pappalardo et al., 2020) leading to create many challenges for food systems and businesses all around the world. In this vein, the

changes in food consumption behavior in the post-COVID era may be related to price increase concerns, food waste awareness, and safety (Güney and Sangün, 2021). This research theme has been mainly focused on stockpiling and food waste during the COVID-19 pandemic (Brizi and Biraglia, 2021), food waste reduction in times of crisis (Malefors et al., 2021), household food waste behavior (Qian et al., 2020), food waste generation (Heikal Ismail et al., 2020), and safety and food packaging (Kitz et al., 2021). Babbitt et al. (2021b) showed that the increased food purchasing behavior of households to gain self-sufficiency during the pandemic has increased waste through bulk purchasing and stockpiling. In another study, Filho et al. (2021) denoted that the COVID-19 lockdowns have resulted in higher consumption levels of take-away food and packaged products. Based on their research evidence, 45–48% of the participants reported consumption growth of fresh food, packed food, and food delivery due to longer stays at home. Nevertheless, despite the potential increase in food waste generated during the pandemic, Vittuari et al. (2021) showed a considerable reduction in declared household food waste due to uncertainty and increased availability of time at home by Italian households. Moreover, the research conducted by Ben Hassen et al. (2021) revealed that although the pandemic has increased the consumption levels of local food products due to food safety concerns, it has improved the awareness of people towards food, leading to food waste reduction.

The second identified research theme focuses on personnel safety and training for waste handling (cluster #2). The main terms included in this cluster are healthcare worker, infectious disease, staff, diagnosis, personnel, professional, training, medical staff, and the healthcare system. The critical role of healthcare sector staff in providing adequate infection control and proper medical WM procedures was underlined by Aleanizy and Alqahtani (2021) to highlight the importance of knowledge and awareness regarding COVID-19 infection control and WM activities in healthcare

facilities. In addition to healthcare personnel, workers in other sectors, such as wastewater treatment plans (Zaneti et al., 2021), and municipal waste centers need to be trained regarding safely handling the medical waste generated due to the pandemic outbreak. Sustainability and using the potentials of the circular economy (cluster #3) has constructed the third research theme of WM research taking COVID-19 into account in the target literature. The circular economy approach, as a tool to promote sustainable development at the local and global scales, has gained momentum (Shevchenko et al., 2021c, 2021a). In this regard, sustainability, supply chain, recycling, circular economy, resilience, raw material, reuse, and sustainable development goal have appeared frequently within the context of research in this area. Developing circular networks and creating circularity to reduce waste, and to return resources to the production cycle was proposed by Alonso-Muñoz et al. (2021), as a cure to make the supply chains resilient against the pandemic adverse effects. Designing eco-design process of face masks based on circularity and life cycle assessment (Boix Rodríguez et al., 2021), recycling of the materials of the disposable filtering masks (Battegazzore et al., 2020), the potential of agri-food loss and waste to contribute to a circular economy (Osorio et al., 2021), blockchain-based forward supply chain and WM practices for COVID-19 medical equipment and supplies (Ahmad et al., 2021), safe WM during the pandemic and circular economy implementation (Pikoń et al., 2021), and the interplay of industry 4.0 and circular economy for developing a smart healthcare waste disposal system (Chauhan et al., 2021) have constructed the bottom line of this research theme. In this regard, smart cities with a special focus on using smart technologies, such as Internet of Things, big data analytics, and cyber-based decision support systems can better support solving WM problems (Shevchenko et al., 2021b).

Personal protective equipment and plastic waste (cluster #4) has been identified as one of the prominent research clusters in COVID-related WM research. The major keywords and terms in this research themes are mask, face mask, plastic, plastic waste, landfill, contaminant, plastic pollution, surgical mask, polymer, and disposable mask. The high demand for personal protective equipment such as face masks, as the main equipment to protect humans against the pandemic, has led to approximately 1.6 million tons/day of plastic waste worldwide (Boix Rodríguez et al., 2021). Consequently, the disposal of such an unprecedented amount of personal protective equipment has posed significant challenges to WM practitioners and societies (Nowakowski et al., 2020), such as environmental pollution (Lee et al., 2021), recycling difficulties (Maderuelo-Sanz et al., 2021), redesigning and reduction of single-use plastics and personal protective equipment (Patrício Silva et al., 2020), and threat to the marine environment and coastal regions (Chowdhury et al., 2021; Dharmaraj et al., 2021). Rizan et al (2021) reported a total of 106,478 tonnes of CO_2 emission as the carbon footprint of distributing personal protective equipment during the first six months of the COVID-19 pandemic in England. Their scenario modeling of environmental mitigation strategies showed that UK manufacture would have reduced the carbon footprint by 12%, reusing gowns and gloves by 10%, eliminating gloves by 45%, and maximal recycling by 35%. However, imposing strict regulations for the public to properly dispose of face masks has become a significant challenge for governments worldwide (Dharmaraj et al., 2021). This highlights the importance of proposing effective and innovative solutions for face mask WM (Rehman and Khalid, 2021), such as using biodegradable materials in face mask production, recycling by obtaining liquid fuels through pyrolysis, and encouraging reusable and washable masks (De-la-Torre et al., 2021; Haddad et al., 2021).

The next research theme belongs to healthcare waste management practices (cluster #5) which is in line with the previous research theme. The main focus of the research included in this cluster is on challenges imposed by the pandemic outbreak on the healthcare facilities. In this vein, terms such as medical waste, waste generation, waste disposal, incineration, infectious waste, transportation, biomedical waste, healthcare waste, and hazardous waste have occurred frequently within the titles and abstracts of the research articles. In this cluster, the importance of proper healthcare waste management has been highlighted by many scholars in terms of controlling the environmental transmission of COVID-19 (Shammi et al., 2021), perception and attitudes towards medical waste disposal (Islam et al., 2020), water, sanitation, hygiene, and waste disposal practices as COVID-19 response strategies (Islam et al., 2021), energy generation from hazardous waste during the pandemic (Valizadeh et al., 2021), selection of the best healthcare waste disposal techniques (Manupati et al., 2021), bio-medical waste incineration (Thind et al., 2021), assessment of healthcare waste disposal technologies in terms of energy, environment, and economy (Zhao et al., 2021), and healthcare waste separation behavior (F. Chen et al., 2021). Wastewater management (cluster #6) and COVID-19 transmission through infectious waste (cluster #7) are considered as the mainstream research frontier regarding the prevention of SARS-CoV-2 transmission. The main terms within the wastewater management research theme are wastewater, detection, surveillance, concentration, wastewater treatment plant, and sewage. On the other hand, presence, route, exposure, particle, surface, droplet, sludge, and aerosol are some of the main terms in the research theme of COVID-19 transmission through infectious waste. The research in these clusters have principally investigated the concentration of SARS-CoV-2 in wastewater (Cao and Francis, 2021), wastewater surveillance (Róka et al., 2021), Monitoring changes in COVID-19 infection using wastewater-based epidemiology (Pillay et al., 2021), SARS-CoV-2 transmission

channels (Abd El-Wahab et al., 2020), and occupational exposure to SARS-CoV-2 in wastewater treatment plants (Dada and Gyawali, 2021).

4. Research agenda: gaps and potential avenues

According to the performance indicators and thematic structures provided in the previous section through the bibliometric and text mining analyses, to address our third research question, we identified the following main research gaps and potential directions as the research agenda for WM post COVID-19:

- ***Adopting a system thinking approach for WM practices***. As highlighted by Naughton (2020), there is a need for more real-time WM data and systems thinking approach regarding COVID-19 effects on waste generation and composition. However, due to the causal-effect links of the interconnected challenges imposed by the pandemic on WM activities, there is still a significant gap in the literature. This requires establishing a systemic framework to monitor and properly manage the pandemic crisis implications for WM practices as a whole. Accordingly, modeling and simulating the long-term effects of COVID-19 on waste generation and formulating appropriate policies are highly recommended for future research. The outputs of such research not only are helpful for COVID-19-recovery plans but also can be generalized and used as a guideline for handling similar crises in the future.

- ***Enabling circular economy framework***. On one hand, the outbreak of the COVID-19 pandemic has led to an unprecedented demand for using personal protective equipment, in particular face masks, which generate a huge amount of waste across the globe. On the other hand, due to the infectious nature of the generated healthcare waste, reusing, repairing, and recycling programs

of such waste have faced serious challenges. Although limited research has been conducted on the potential of circular economy approaches to mitigate the effects of the pandemic on waste (Kumar et al., 2021; Pikoń et al., 2021; Sharma et al., 2021), research in this area is still in its immaturity stage and so far from practice and implementation in the real world. Therefore, building a circular economy framework from the design stage to the implementation stage is of high importance to effectively deal with COVID-related waste. On this basis, (i) innovative solutions to keep materials and products within the cycle as long as possible, (ii) consumer contribution to the circular economy transition in the healthcare industry, and (iii) developing smart and network-based WM systems to support WM activities towards a circular economy focusing on waste prevention and reduction, are proposed as potential avenues for further research in WM research agenda post COVID-19.

- ***Extending government-led incentives***. In line with the research conducted by Sharma et al. (2021), decentralization of WM systems and practices with a bottom-to-top approach is recommended for policy-makers and authorities to better manage the newly emerged waste post the pandemic. We believe that there is no better time than now to plan for involving local communities in the WM activities. In this regard, developing encouraging plans and incentives to effectively involve informal sectors and local capacity in municipal waste management, especially in developing and less-developed countries, remarkably deserves to be deeply investigated in future research.

Fig. 8 summarizes the main directions for future research on WM practices in the wake of the pandemic.

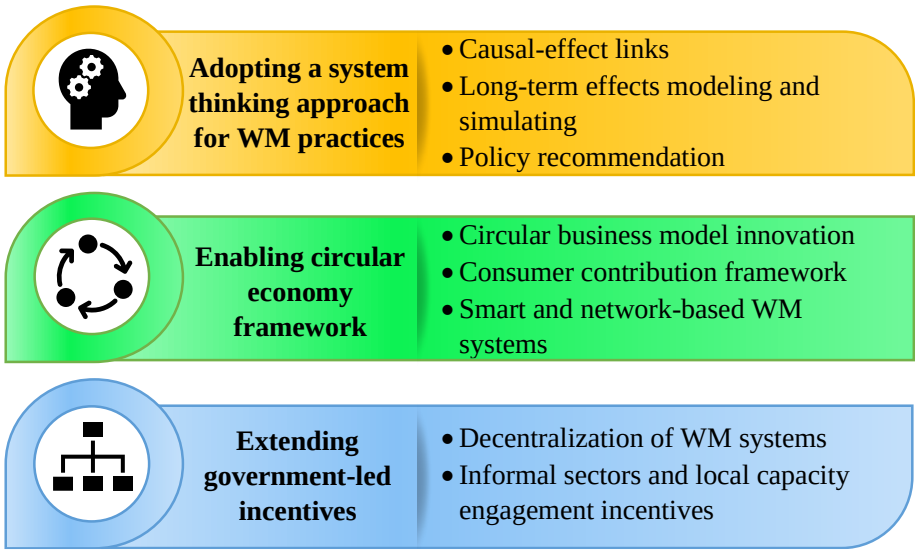


Fig. 8. Future research agenda for WM research post COVID-19 era.

5. Conclusion

This study provided an inclusive map of the WM research in the context of the COVID-19 pandemic by conducting bibliometric and text mining analyses on a total of 1030 peer-reviewed journal articles in the Scopus citation database. As a result, the performance of the COVID-related scientific production in the WM field was mapped through analyzing and discussing bibliometric performance indicators, including (i) geographical distribution of publications, (ii) authors productivity and influence, (iii) main contributing journals and publications, and (iv) keyword-based analysis to unfold research tendencies and hotspots. Besides, by conducting bibliographic coupling, the following three main clusters of research in WM post COVID-19 were identified: (a) plastic waste generation and management during the pandemic, (b) detection of COVID-19 in wastewater, and wastewater surveillance during the pandemic, and (c) potential spread of COVID-19, disinfection strategies and their associated challenges. The salient research themes of the target literature were also identified by conducting text mining analysis on the titles and abstracts of the

519 articles as follows: (1) household and food waste, (2) personnel safety and training for waste
520 handling, (3) sustainability and circular economy, (4) personal protective equipment and plastic
521 waste, (5) healthcare waste management practices, (6) wastewater management, and (7) COVID-
522 19 transmission through infectious waste.

523 The provided insights support researchers and policy-makers to better understand the effects of the
524 pandemic on generating various waste streams and emerged challenges for WM practices and
525 activities. As such, a research agenda based on the main research gaps was proposed for further
526 studies, focusing on (i) system thinking approach to properly manage the pandemic crisis
527 implications for WM practices as a whole, (ii) building a circular economy model from the design
528 stage to the implementation stage, and (iii) proposing incentives to effectively involve informal
529 sectors and local capacity in decentralizing municipal waste management, especially for
530 developing and less-developed countries. Nevertheless, there are some limitations to this research.
531 First, the sample data was retrieved from the Scopus database. Therefore, incorporating other
532 databases, such as Web of Science, may enhance the reliability of the present research and further
533 extend the findings. Second, non-English documents were excluded from our search, potentially
534 missing some specific studies and practices in WM at a micro-level.

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