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REVIEW ARTICLE

Emerging trends in municipal solid waste incineration ashes research: a bibliometric analysis from 1994 to 2018

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Abstract

The rapidly increasing generation of municipal solid waste (MSW) threatens the environmental integrity and well-being of humans at a global level. Incineration is regarded as a technically sound technology for the management of MSW. However, the effective management of the municipal solid waste incineration (MSWI) ashes remains a challenge. This article presents the global dynamics of MSWI ashes research from 1994 to 2018 based on a bibliometric analysis of 1810 publications (research articles and conference proceedings) extracted from the Web of Science database, followed by a comprehensive summary on the research developments in the field. The results indicate the rapid growth of annual publications on MSWI ashes research, with China observed as the most productive country within the study period. Waste Management, Journal of Hazardous Materials, Chemosphere and Waste Management & Research, which accounted for 35.42% of documents on MSWI research, are the most prominent journals in the field. The most critical thematic areas on this topic are MSWI ashes characterisation, dioxin emissions from fly ash, valorisation of bottom ash and heavy metal removal. The evolution of MSWI ashes treatment technologies is also discussed, together with the challenges and future research directions. This is the first bibliometric analysis on global MSWI ashes research based on a sufficiently large dataset, which could provide new insights for researchers to initiate further research with leading institutions/authors and ultimately advance this research field.

Keywords Circular economy · Resource sustainability · Closed-loop recycling · Microwave-assisted hydrothermal treatment · Polychlorinated dibenzo-p-dioxins · Polychlorinated dibenzofurans

Introduction

Technological developments, explosive population growth, and the growing trend in consumerism have resulted in a drastic increase in global municipal solid waste (MSW) generation. The World Bank reported a global MSW production of 2.01 billion tonnes in 2016, with a projected generation of 3.40 billion tonnes in 2050 (Kaza et al. 2018). Given this scenario, MSW management is considered an essential service provided by local municipalities (Hoornweg and Bhada-Tata 2012). In the last decade, the disposal of MSW in sanitary landfills was considered the most acceptable option to replace open dumping (Ghosh et al. 2019).

Nevertheless, MSW incineration (MSWI) has gained popularity after its introduction in the nineteenth century. Typically, MSWI requires less land space and contributes less to global warming compared to landfills (Makarichi et al. 2018). At present, MSWI is considered the most essential element in the integrated MSW management system. The

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process dramatically reduces the weight and volume of MSW (Li et al. 2017). It can effectively extend the lifespan of landfills, which is typically the last destination for waste deposition (Istrate et al. 2019). In addition, the latest waste-to-energy (WtE) incineration plants utilise state-of-the-art technologies to convert MSW into the heat and energy required for electricity generation. The thermal heat recovered during the MSWI can also be used for energy generation. Therefore, the process complies with the "closing the loop" concept emphasised in the circular economy (Tomić and Schneider 2018). MSWI is commonly regarded as a practical solution to MSW management and renewable energy generation (Istrate et al. 2019). A total of 1179 MSW incinerators have been built in different countries at present, with a total capacity of 7×10^5 metric tonnes/day (Lu et al. 2017). Therefore, it is projected that MSW incinerator and WtE plants will remain critical elements in MSW management system.

Despite the benefits of MSWI mentioned above, the presence of various contaminants in the bottom ash (BA), fly ash (FA) and other residues pose threats to the human health, safety and the environment. Thus, the wide-scale adoption of MSWI is possible only with proper pretreatment of the secondary wastes before disposal in designated landfills. In addition, following the rapidly increasing stockpiles of MSW, it is foreseen that more land will still be required for the safe disposal of MSWI ashes. The predicted scenario could add stress to countries that adopt MSWI due to issues such as land scarcity. Therefore, the focus of MSWI ashes management has shifted from safe disposal in landfills to recycling and valorisation based on efficient technologies. Currently, the recycling of BA and FA from different sources, including MSWI, has been implemented in many European countries, while research teams are developing more environmentally friendly approaches to recycle MSWI ashes (Tang et al. 2018c). Joseph et al. (2018) showed that MSWI BA/FA valorisation and recycling are currently the hot research topics in solid waste management. As such, the growing developments in the field have been recently reviewed by several scientists, as listed in Table 1. Therefore, a detailed examination of the recent research and publication trends on MSWI ashes research will significantly benefit the scientists in this field.

Following the rapid growth in science, various metrics (such as bibliometrics, scientometrics and informetrics) have been developed to examine the dynamics in different research disciplines. These three metrics share some similarities in terms of objectives, methods or tools. Nevertheless, scientific publications related to bibliometric studies greatly outnumber the other two (Siluo and Qingli 2017). Many studies have highlighted the inadequacy of using bibliometric analyses to determine the productivity and impacts of a researcher/institution/country related to a specific research topic. Nevertheless, this analysis remains one of the most practical, accessible and recognised tools in the academic world (Aleixandre-Tudo et al. 2019; Hall 2011).

Therefore, this paper reviews the recent developments in MSWI ashes research through a bibliometric analysis of the scientific publications produced from 1994 to 2018. The general trends in published research articles and proceedings (collectively termed as documents in this study) are analysed in terms of annual outputs, journal distributions, top-cited papers, funding agencies, as well as the most productive countries, organisations and authors. Social network analysis was also performed to illustrate the collaborative works at country and organisation levels, followed by the co-occurrence of keywords contained in the selected documents. To the best of the authors' knowledge, this is the first bibliometric study on MSWI ashes research in literature that provides readers with a state-of-the-art overview of the current research and publication scenario on the topic.

Methodology

Web of Science (WoS) is one of the most elaborate citation indexing services for scientific and scholarly research. It contains over 20,000 high-quality journals spanning different disciplines such as engineering, social science, science, humanities, among others. The development of WoS greatly facilitates researchers' efforts in studying the progress of a research topic at the meta-level (discipline), meso-level (journals, institutions) and micro-level (individuals) (Hall 2011). Typically, the documents published by the journals listed in WoS are indexed explicitly, enabling researchers to trace the flow of ideas based on time, geographical locations, institutions and disciplines (Joseph et al. 2018). On 7/5/2019, an advanced search was made in WoS using the following search string: "TS = ((mswiba OR mswifa) OR (("municipal solid waste" OR "msw" OR "municipal solid waste incinerat*" OR "mswi") AND ("fly ash*" OR "bottom ash*" OR fa OR ba)))", with a time span from 1994 to 2018. Some terms in the search string were ended with asterisks to ensure all the terms with the same root are included in the search result (Aleixandre-Tudo et al. 2019; Skute 2019). The adopted search string ensured all the documents related to the following research questions:

1. What are the physicochemical properties of the ashes produced from MSWI, and the factors that influence these properties?
2. What are the effects of these ashes on the MSW incinerator, equipment and environment?
3. What are the possible methods to minimise the negative impacts of MSW ashes on the incinerator and environment?
4. What is the current progress in the treatment, recycling, reuse and valorisation of MSW ashes?

Table 1 Review papers on recycling of MSWI BA and FA

Ref	Focus
Zhenghui et al. (2019)	Appropriate strategies for handling and valorisation of MSWI BA, FA and air pollution control unit residue
Joseph et al. (2018)	Statistics on municipal solid waste (MSW) incineration ashes in Belgium, together with the recent development in MSW ash pretreatment technologies and applications of pre-treated ash as construction materials.
Xuan et al. (2018a)	Environmental and engineering concerns in replacement of natural aggregates by MSWI BA for different applications
Fan et al. (2018)	Stabilisation/solidification of heavy metals in MSWI FA in different cements.
Dou et al. (2017)	Utilisation of MSWI BA for different applications
Meer and Nazir (2017)	Various heavy metal removal techniques from FA originated from combustion of coal, municipal solid waste etc.
Silva et al. (2017)	Applications of MSWI BA in synthesis of adsorbents, production of ceramics, landfill cover and biogas production enhancer.
Verbinnen et al. (2016)	Challenges and prospects in recycling of MSWI BA

Consequently, the documents that fulfilled the search criteria were retrieved from the Web of Science Core Collection (SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, BKCI-S, BKCI-SSH and ESCI). Only the articles and conference proceedings were included in the analysis since these documents provide original findings on MSWI ashes research (Song et al. 2019; Xing et al. 2019). The title, abstract, author keywords, KeyWords Plus and contents of all documents were further examined to ensure the selected documents address at least one of the research questions. Most of the documents that were eliminated from the initial search results are related to the following topics: (1) melting/gasification/pyrolysis/composting of MSW; (2) ashes produced from the incineration of coal, sewage sludge, hospital waste, industrial waste, hazardous waste, tannery sludge but not related to MSW; and (3) formation and transport of air pollutants and leachate in or after MSW incineration, and proposed solutions for such pollutants.

As shown in Fig. 1, a total of 1810 documents were selected for bibliometric analysis in this study. The data analysis procedure, as adapted from Wu et al. (2019), was divided into three stages: (1) quantitative analysis on the publication trend on MSWI ashes research; (2) social network analysis to demonstrate the research collaborations among countries, organisations; and (3) co-occurrence analysis of Keywords Plus to determine the research focus. Consequently, the discussion was supported with the impact factors and h-indices of journals, authors, organisations and countries, which were also extracted from WoS to illustrate the associated productivities and impacts. The impact factor of a journal is calculated based on the number of citations received for the recent articles published in the journal. On the other hand, h-index, or Hirsch index (Hirsch 2005) of scientists, journals, organisations and countries are defined based on the most cited documents and the number of citations received in other documents. The full citation records of the selected documents were also exported from WoS into ".txt" files for analysis using BibExcel (publication trend in different periods) and VOSViewer (for the social network analysis and keyword analysis).

Results and discussion

General publication trend

As observed, the selected documents are closely related to the characteristics and effects of MSWI BA/FA on the environment, along with valorisation methods used to minimise the adverse effects. Due to the similar generation source and compositions, documents that discussed the air pollution control unit ash and boiler ash in MSW incinerators were also included. The selected documents received 34,018 citations (including self-citations) up to December 2018. Therefore, the average citations per item were calculated to be 18.78.

As shown in Fig. 2 and Table 2, the number of articles related to MSWI ashes increased swiftly from 21 (in 1994) to 212 (in 2018), due to increased research funding on MSWI ashes research. As shown in Table S1, the top five funding agencies are all located in China, following the addition of resources conservation and environmental protection into the national plan of China (Zhai and Chang 2019). The commencement of financial support from these agencies resulted in the rapid development of MSWI ashes research in China from 2012 to 2018. In contrast to the rapid increase in the annual number of research articles, the annual proceedings output fluctuated between 1 and 27, but no obvious trend could be observed. English was used in 1784 articles (98.5%), making it the dominant language in the documents extracted from WoS. Other languages used include Japanese (15), German (4), Spanish (3), Polish (2), French (1), Portuguese (1) and Slovenian (1).

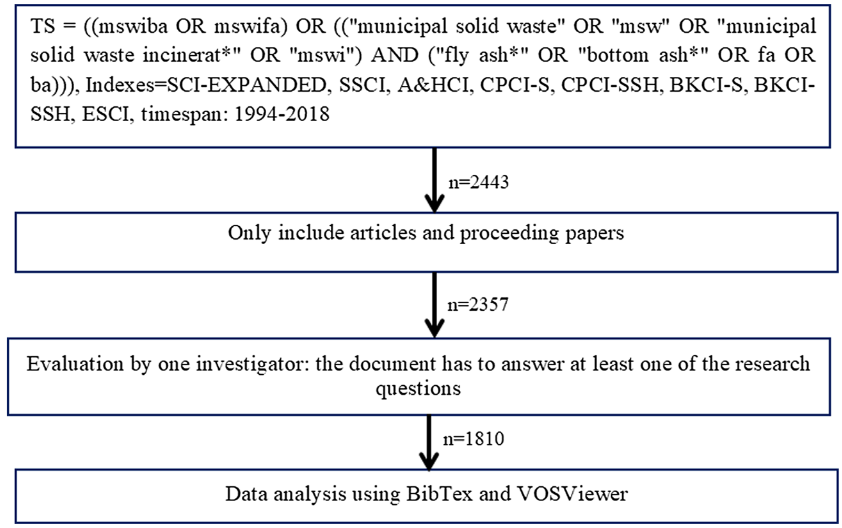

Fig. 1 Selection procedure for bibliometric analysis

The 1810 documents on MSWI ashes research covered 83 WoS categories, dominated by Environmental Sciences (1152, 63.6%) and Environmental Engineering (852, 47.1%). The substantial increase in the documents in these categories from 1994 to 2018 (Fig. 3) demonstrates the intense focus of scientists on the environmental impacts caused by the ashes. Consequently, the trend has led to the development of various valorisation methods to minimise the impacts of the ashes. In comparison, the percentage contributions of Material Science, Multidisciplinary, Chemical Engineering and Energy & Fuels also increased from 1995 to 2008, although to a minor extent. The documents in these categories are related to physical factors and process parameters (during MSWI) that affect the contaminant levels in MSWI ashes, as well as characterisations of ashes and valorised products.

According to WoS, all the analyzed documents produced in 1994–2018 were published in 484 peer-reviewed journals and proceedings. According to Bradford's Law, Waste

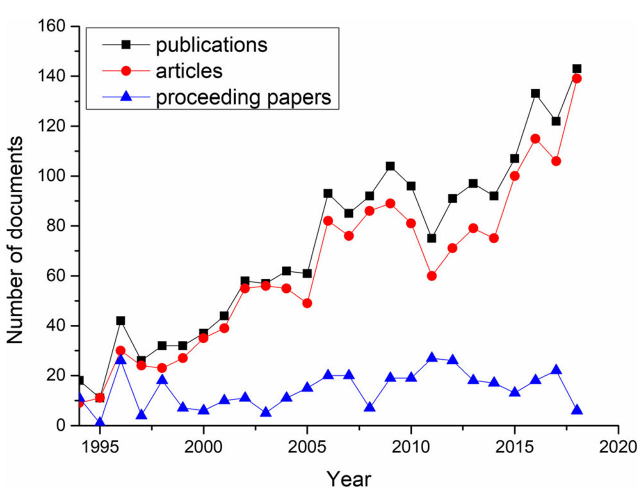

Fig. 2 Annual publications on MSWI ashes research in 1994–2018

Table 2 Characteristics of annual publications in 1994–2018 (TP = total number of publications, NR/TP = average number of references for each document, TC/TP = average number of citations for each document, PG/TP = average page number for each document, AU/TP = average number of authors for each document)

Year	TP	NR/ TP	TC/ TP	PG/ TP	AU/ TP
1994	21	9.67	15.89	12.11	3.33
1995	14	19.18	59.45	10.36	3.36
1996	46	10.24	28.17	9.00	2.48
1997	29	17.00	29.65	10.85	2.88
1998	47	13.87	20.06	8.94	2.66
1999	43	20.91	36.97	11.81	3.25
2000	43	17.97	42.92	9.16	3.11
2001	50	18.07	30.16	9.30	2.86
2002	67	21.50	38.50	9.10	2.95
2003	71	22.47	30.65	9.67	2.95
2004	73	21.50	33.27	8.40	3.34
2005	74	19.33	26.29	8.46	3.05
2006	112	25.45	32.46	9.20	3.43
2007	105	22.67	21.94	8.33	3.44
2008	119	26.54	22.04	8.26	3.60
2009	141	26.86	24.30	7.34	3.28
2010	133	25.27	19.32	7.63	3.58
2011	103	26.57	15.69	7.88	3.45
2012	131	27.15	15.54	7.43	3.52
2013	152	29.32	14.41	7.70	3.81
2014	136	31.29	8.91	8.00	3.67
2015	166	33.68	11.10	9.21	3.87
2016	199	36.60	7.33	9.27	3.65
2017	198	36.52	4.66	9.70	3.75
2018	212	42.07	1.72	10.28	3.81

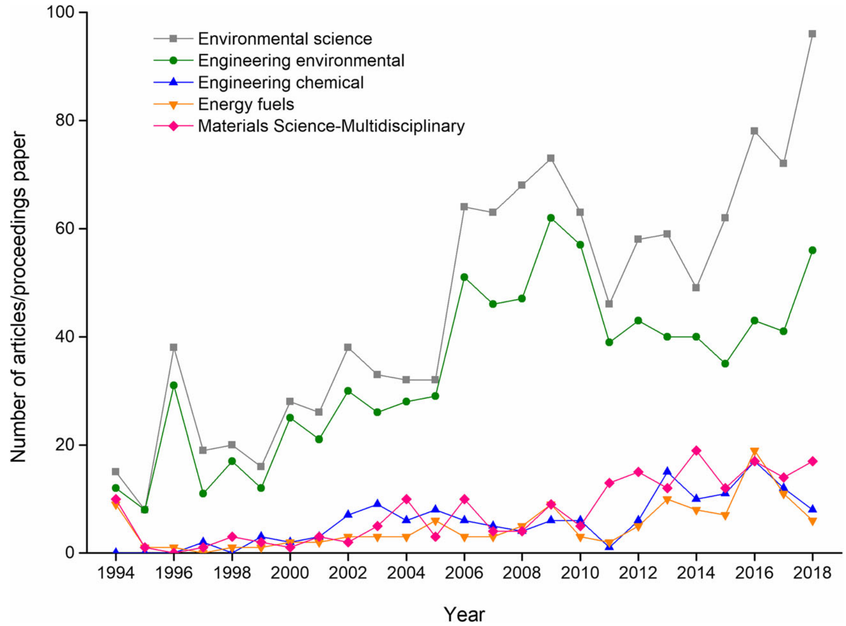

Fig. 3 Major WoS categories for MSWI ashes research in 1994–2018

Management, Journal of Hazardous Materials, Chemosphere, as well as Waste Management & Research are identified as the core journals for documents published on MSWI ashes research. Hence, the cumulative percentage of documents published in the outlined journals is 33% (Lei et al. 2019). In addition, the top ten productive journals contain 850 documents or 46.98% of the total number of documents (Table 3). These journals focus on different thematic areas. Waste Management, Journal of Hazardous Materials alongside Waste Management & Research published articles on sustainable management of MSWI ashes (as hazardous materials) through the application of different technologies.

On the other hand, the documents published in Chemosphere, Environmental Science & Technology, Science of the Total Environment, along with Environmental Science and Pollution Research focus on the adverse impacts exerted by MSWI ashes on the environment (air, water, soil among others) and potential mitigation measures. The journals Construction and Building Materials and the Advanced Materials Research published studies on the characteristics

Table 3 Top ten productive journals on MSWI ashes research

Journal	TP	IF (2017)	h-index (2017)	Categories (position)	Percentage of total	Cumulative percentage of total (%)
Waste management	282	4.723	46	Engineering, Environmental (Q1/9/50); Environmental Science (Q1/25/242)	15.58	15.58
Journal of Hazardous Materials	181	6.434	50	Engineering, Environmental (Q1/5/50); Environmental Science (Q1/13/242)	10.00	25.58
Chemosphere	106	4.427	28	Environmental Science (Q1/35/242)	5.86	31.44
Waste Management & Research	72	1.631	16	Engineering, Environmental (Q3/33/50); Environmental Science (Q3/146/242)	3.98	35.42
Environmental Science and Technology	61	6.653	31	Engineering, Environmental (Q1/4/50); Environmental Science (Q1/11/242)	3.37	38.79
Construction and Building Materials	41	3.485	14	Construction and Building Technology (Q1/10/62); Engineering, Civil (Q1/11/128); Materials Science, Multidisciplinary (Q2/72/285)	2.27	41.06
Advanced Materials Research	29	–	3*	–	1.60	42.66
Environmental Science and Pollution Research	28	2.800	6	Environmental Science (Q2/83/242)	1.55	44.21
Science of the Total Environment	28	4.610	17	Environmental Science (Q1/27/242)	1.55	45.76
Energy and Fuels	22	3.024	8	Energy & Fuels (Q2/40/97), Engineering, Chemical (Q2/36/137)	1.22	46.98

*Generated based on citation report function in Web of Science and applications of various construction materials (cement, concrete, brick, geopolymers, among others) derived from MSWI ashes. The documents published in Energy & Fuels focus on the use of MSW as an energy source, with ashes as the by-products that require proper treatment.

Figure 4 (with further descriptions in Section S1) displays a network visualisation map that illustrates the co-citation relationship among the journals listed in Table 3. The absence of Advanced Materials Research in the map was observed as it has no citation relationship with other journals. The strongest co-citation relationship can be observed between Waste Management and the Journal of Hazardous Materials, as both journals focus on the management and valorisation of MSWI as hazardous materials. Similarly, a strong co-citation relationship exists between Chemosphere and Environmental Science & Technology, as both journals publish documents related to the effects of MSWI ashes on the environment.

Table 4 lists the top ten highly cited papers related to MSWI ashes, which were published in the years 1995–2005. Due to the chronologic tendency of citations as observed by Lei et al. (2019), most of the recent publications receive a lower number of citations than others listed in Table 4. The most cited paper was published by Abbaspour et al. (2004) that demonstrated the use of an uncertainty fitting procedure in the estimation of uncertain flow in MSWI BA monofills. The paper was published in the Vadose Zone Journal and received 347 citations up to the year 2018. Everaert and Baeyens (2002) studied the possible factors that lead to dioxins production during MSWI based on the data of a Flemish MSW incinerator. The study concluded that temperature in the electrostatic precipitator is the only significant factor. Sabbas et al. (2003) and Hjelmar (1996) presented overviews on the long-term management of MSWI ashes, mainly BA and air pollution control residues. The potential for converting MSWI ashes into useful products was discussed and demonstrated by Ferreira et al. (2003) and Gupta et al. (2005), respectively. The efforts to characterise electrostatic precipitator ash collected from a Canadian MSW incinerator (Eighmy et al. 1995), as well as MSWI BA, collected from two MSWI in Spain (Chimenos et al. 1999) provided valuable information to other researchers on suitable treatment or valorisation methods for MSWI ashes. Meima and Comans (1997) provided extensive analysis on the contaminants leaching from aged MSWI BA, while (Park and Heo 2002) characterised the glass produced from the vitrification of MSWI FA produced in a Korean MSW incinerator.

Contribution and collaborations among countries

The contributions from the top ten countries on MSWI ashes research in 1994–2018 are displayed in Table 5. The USA was the most productive country from 1994 to 1998 with 25 documents. However, Japan surpassed the USA from 1999 to 2003 as the most productive country with 36 documents. The fast-increasing productivity by China from 1 document (in 1994–1998) to 269 documents (in 2014–2018) was observed due to increased research funding, as discussed in the "General publication trend" section 3.1. With this performance, China became the most productive country from 1994 to 2018 with a total of 513 articles (28.3%) and h-index of 37. The high productivity demonstrates the commitment of the Chinese government to addressing the adverse

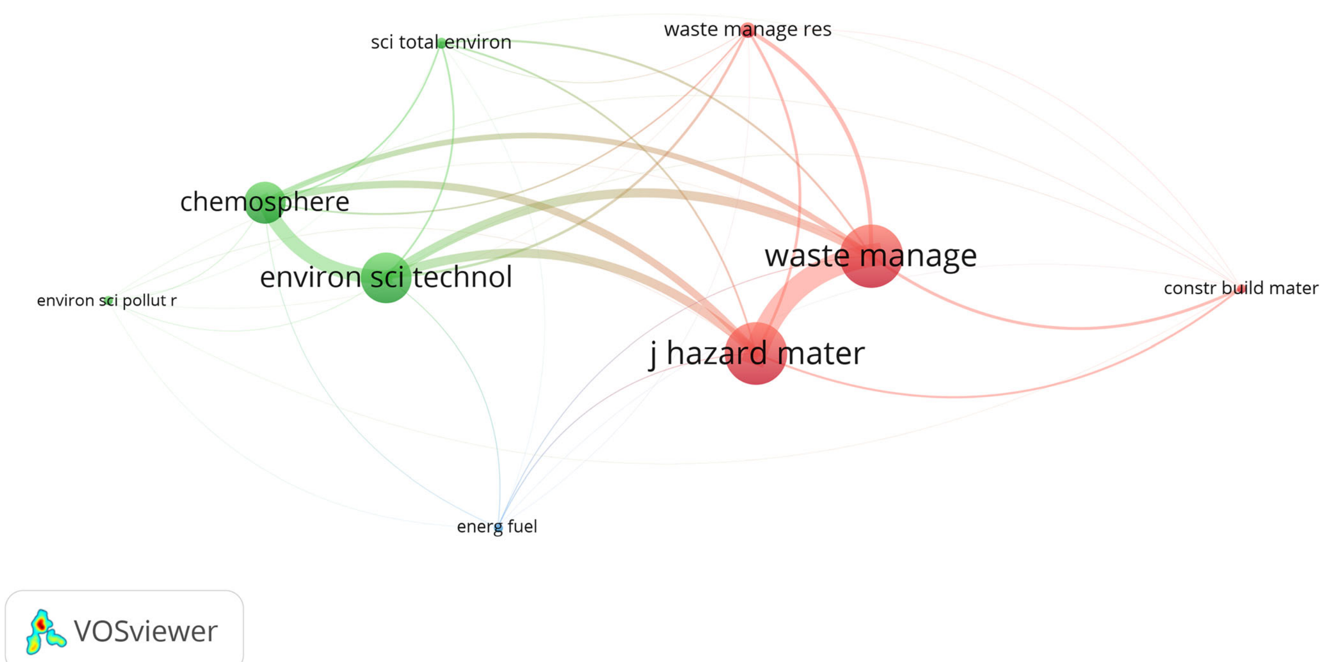

Fig. 4 Co-citation relationship among the top nine journals on MSWI ashes research

Table 4 The most highly cited documents on MSWI ashes research in 1994–2018

Title	Ref	Journal	TC
Estimating uncertain flow and transport parameters using a sequential uncertainty fitting procedure	Abbaspour et al. (2004)	Vadose Zone Journal	348
Management of municipal solid waste incineration residues	Sabbas et al. (2003)	Waste Management	257
Possible applications for municipal solid waste fly ash	Ferreira et al. (2003)	Journal of Hazardous Materials	228
Comprehensive approach towards understanding element speciation and leaching behaviour in municipal solid-waste incineration electrostatic precipitator ash	Eighmy et al. (1995)	Environmental Science and Technology	205
The formation and emission of dioxins in large scale thermal processes	Everaert and Baeyens (2002)	Chemosphere	204
Removal of dyes from wastewater using bottom ash	Gupta et al. (2005)	Industrial and Engineering Chemistry Research	192
Geochemical modelling of weathering reactions in municipal solid waste incinerator bottom ash	Meima and Comans (1997)	Environmental Science and Technology	183
Vitrification of fly ash from municipal solid waste incinerator	Park and Heo (2002)	Journal of Hazardous Materials	176
Disposal strategies for municipal solid waste incineration residues	Hjelmar (1996)	Journal of Hazardous Materials	174
Characterisation of the bottom ash in municipal solid waste incinerator	Chimenos et al. (1999)	Journal of Hazardous Materials	173

impacts of MSW resulting from the rapid urbanisation and developments that have occurred in China in recent decades. According to the World Bank Group (2017), China is currently generating 520,548 tonnes of MSW/day, which will increase to 1,397,755 tonnes of MSW/day in 2025. Realising the immediate urgency to address the issue, the Chinese government has allocated more resources, particularly research funds to support the development of MSW incineration technologies as a solution to the MSW management in large cities (Kaza et al. 2018).

The publications produced by Italian scientists also increased steadily from 7 (1994–1998) to 54 documents (2014–2018), although at a slower rate of increase compared to China. Similarly, Japan, Taiwan, France and South Korea displayed increased productivities at different periods but decreased in 2014–2018. This trend could be due to the relatively matured status of MSWI and the ash management technologies in these countries, which requires less need for research on the topic.

The advancement in communication technology enables a higher degree of international and intercontinental research collaborations, which subsequently enhances the transfer of knowledge and technology across nations. The number of publications on MSWI ashes (minimum number: 15 documents per country) is due to collaborations among twenty countries as illustrated in Fig. 5 (further descriptions in Section S1), except for the isolated node. China published the most documents (117) out of collaborative research with the other countries, as observed in Fig. 5, followed by Japan (48), USA (48), Netherlands (32) and Denmark (31). Cross-examination with the data in Table 5 shows that international collaboration plays an important role in MSWI ashes research. As observed, countries like the USA, South Korea, Canada, Switzerland and France

Table 5 Top ten productive countries on MSWI ashes research

Country	TP	h-index	Number of documents				
			1994–1998	1999–2003	2004–2008	2009–2013	2014–2018
China	513	37	1	5	65	173	269
Japan	213	32	23	36	61	46	47
Taiwan	183	34	7	22	55	66	33
Italy	172	32	16	24	26	52	54
USA	103	27	25	24	14	11	29
Sweden	101	26	4	16	31	19	31
France	91	30	7	28	29	17	10
Netherlands	67	25	16	8	12	17	14
South Korea	65	20	1	15	33	9	7
Germany	62	20	9	14	9	12	18

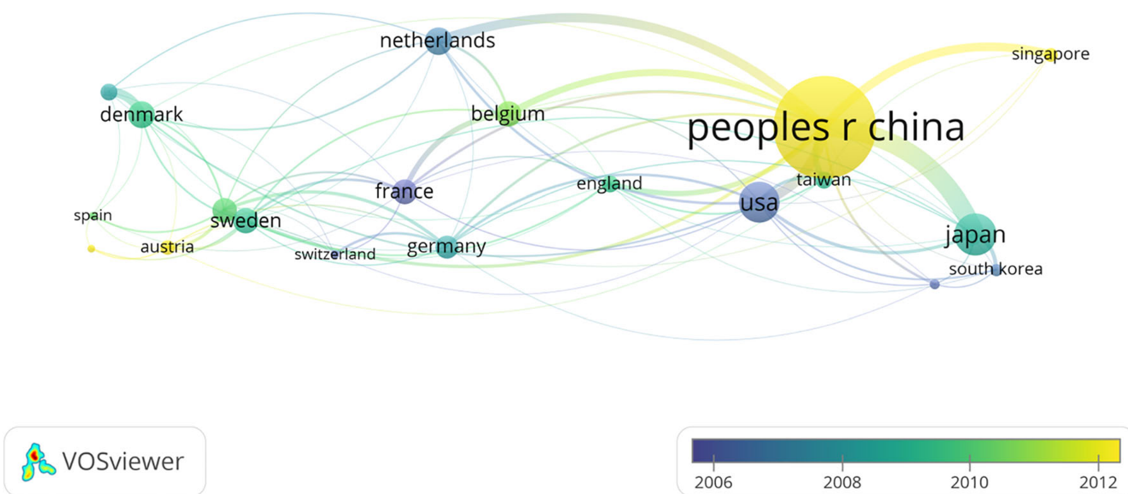

Fig. 5 International collaboration among the top 20 countries (minimum number 15 document per country, excluding the isolated node)

are among the countries that contributed to the early international collaborative research related to MSWI ashes. Following the time progression, more countries adopted incineration technology in MSW management, and knowledge transfer occurred through international collaborations. Most of the recent research collaborations were performed among the researchers from China, Singapore, Australia, Norway, India and countries with advanced technology for MSW incineration.

Contributions and collaborations among organisations

A total of 1125 organisations from different countries have published documents on MSWI ashes research, of which 77 have published 10 or more documents. As shown in Table 6, seven out of the ten top productive countries in MSWI ashes research are located in Asia, whereas the other three are in Europe. A network visualisation map (Fig. 6, with further descriptions in Section S1) was produced using VOSViewer to illustrate the inter-organisational collaborations on MSWI ashes research (with a minimum number of 10 documents). Zhejiang University (China) is deemed the most productive organisation in MSWI ashes research, as evidenced by 78 documents published with 10.62 citations per document (Table 6). From Fig. 6, Zhejiang University has formed strong partnerships with several organisations in China (including Zhejiang Gongshang University, Zhejiang University of Technology, Shanghai University) as well as those in other countries, especially Southeast University (Bangladesh), Lulea University of Technology (Sweden) and Tokyo Institute of Technology (Japan).

Similarly, the high productivity (57 documents) displayed by Tongji University could be attributed to the collaborative research works with Shanghai University, Shanghai Institute of Technology, National Taiwan University, Technical University of Denmark, Delft University of Technology, Tokyo Institute of Technology and Kyushu University. Despite the lower number of documents published, KU Leuven (Belgium) and Technical University of Denmark exert more impacts in the research field, as depicted by their h-indices (17 and 21, respectively) and average citations per

Table 6 Top ten most productive organisations on MSWI ashes research

Organisation (country)	Document (%)	No. citations	Citation/document	h-index
Zhejiang University (China)	78 (4.31%)	835	10.71	16
Tongji University (China)	57 (3.14%)	967	16.96	18
Technical University of Denmark (Denmark)	54 (2.98%)	1610	29.81	21
Kyoto University (Japan)	47 (2.60%)	815	17.34	16
Chinese Academy of Sciences (China)	42 (2.32%)	653	15.55	14
Tsinghua University (China)	41 (2.27%)	800	19.51	15
Chongqing University (China)	39 (2.16%)	128	3.28	6
KU Leuven (Belgium)	31 (1.71%)	1133	36.55	17
Nanyang Technological University (Singapore)	31 (1.71%)	394	12.71	12
University of Brescia (Italy)	28 (1.55%)	452	16.14	14

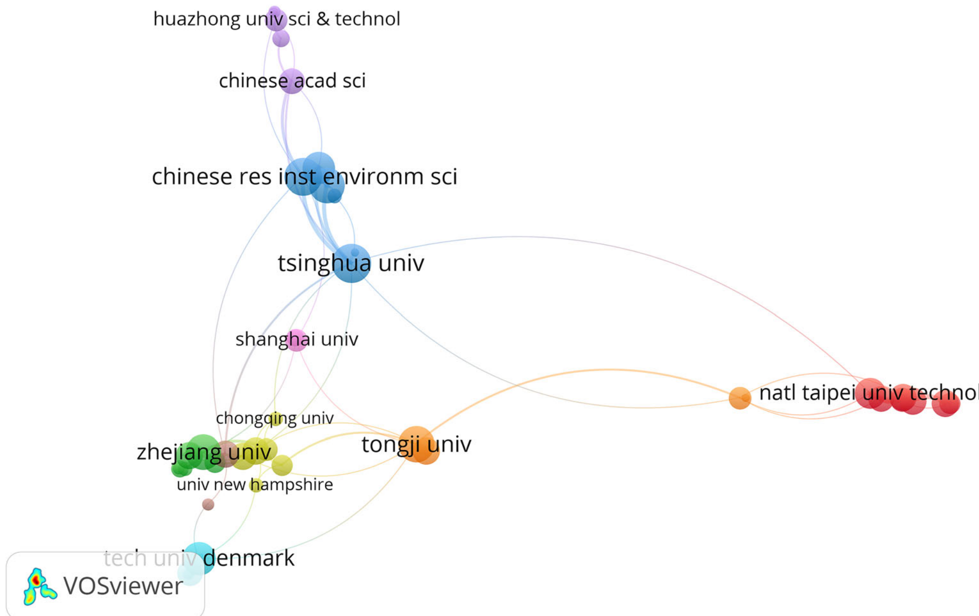

Fig. 6 Co-authorship network among organisations (minimum number of documents: 10, top 43 countries, ignore isolated node, node size represent total link strength)

document (36.55 and 29.81, respectively). Such comparison reveals the shift of the core research region from European countries to Asian countries (especially China), which is also reported by Wu et al. (2019) for construction and demolition waste research.

Most productive and highly cited authors

There were 3778 authors involved in MSWI ashes research and 75 authors among them published 10 or more documents during the studied period. Furthermore, nine out of ten top productive authors (Table 7) are affiliated with Asian institutions. Yan JH, who published 44 documents and attracted 500 citations, is the most productive author in MSWI ashes research. The author's studies focus mainly on polychlorinated dibenzodioxins and polychlorinated dibenzofurans (PCDD/Fs) together with heavy metal emissions produced during MSWI (Chen et al. 2008). The author, together with Lu SY, has contributed to the high productivity of Zhejiang University (China). It is also worth mentioning that Comans RNJ (Netherlands) has the highest h-index (17) and average citations per document (67.60) among all the authors listed in Table 5. The author was active in MSWI ashes research from 1994 to 2013 with four research articles receiving more than 100 citations up to December 2018. The author's works have been mostly related to geochemical modelling and contaminants leaching from MSWI BA during weathering. This was followed by Lin KL from National Ilan University (Taiwan) (also with h-index of 17), who specialises in the treatment and conversion of MSWI FA to cementitious materials.

Co-occurrence analysis

The co-occurrence of any two terms refers to their presence in the same scientific publication (Lancho-Barrantes and Cantu-Ortiz 2019). The examination of the co-occurrence of

Table 7 Top ten most productive authors on MSWI research

Author (country)	Document (%)	No. citation	Citation/document	h-index
Yan JH (Zhejiang U, China)	44 (2.44)	500	11.36	13
Li XD (Jiliang U, China)	37 (2.04%)	527	14.24	13
Takaoka M (Kyoto U, Japan)	37 (2.04%)	466	12.59	13
Lin KL (Natl Ilan U, Taiwan)	36 (1.99%)	773	21.47	17
Lu SY (Zhejiang U, China)	35 (1.93%)	430	12.29	12
Shimaoka T (Kyushu U, Japan)	25 (1.38%)	252	10.08	8
Vandecasteele C (KU Leuven, Belgium)	25 (1.38%)	888	35.52	15
Oshita K (Koto U, Japan)	23 (1.27%)	319	13.87	10
Wang KS (Natl U, Taiwan)	22 (1.22%)	533	24.23	14
Comans RNJ (Wageningen U, Netherlands)	20 (1.11%)	1352	67.60	17

keywords is important to reveal the thematic areas in MSWI ashes research. A total of 2108 KeyWords Plus (termed as keywords in the following discussion) were extracted from 1810 articles using VOSViewer. However, only the most popular keywords (minimum number of occurrence: 50, number of keywords: 29) were included in the visualisation map generated using VOSViewer. As shown in Fig. 7 (further description in Section S1), "fly ash" (occurrence: 322) appears to be the most frequently used keyword, followed by "heavy metals" (254) and "behaviour" (222).

As indicated by different colours in Fig. 7, the keywords are categorised into four major clusters. Cluster 1 (in red colour) represents the characterisation of MSWI ashes, which involves studies on the speciation and leaching behaviour of elements with "heavy metals" (254) as the largest node. This finding indicates that the behaviour of heavy metals in MSWI ashes has been a significant concern in many studies. Cluster 2 (in green colour) is on dioxin emissions from MSWI FA, with the keyword "fly ash" (322) having the highest occurrence. The appearance of "China" as the only country name in this cluster also demonstrates its enormous interest in MSWI ashes management. Cluster 3 (in blue colour) focuses on the valorisation of MSWI BA with the term "behaviour" (222), which appeared most frequently. Various studies explore the potential utilisation of MSWI BA for the production of cement, aggregate and concrete other than direct disposal at landfills. Meanwhile, cluster 4 (in yellow colour) is related to the removal of heavy metals from MSWI ashes to prevent soil and water contamination. It is noteworthy that the keywords "lead" (42), "copper" (43) and "zinc" (40) are the only three heavy metals that appear on the keyword map. This shows that the removal of lead (Pb), copper (Cu) and zinc (Zn) in the MSWI ashes has received more attention compared to other heavy metals.

Discussion

Types of contaminants in MSWI ashes

The incineration of MSW produces about 80 wt% of BA and 20 wt% of FA, which are conventionally disposed of in landfills (Dontriros et al. 2020). Nevertheless, due to the high contents of heavy metals, salts, organic pollutant and soluble salts (mainly chlorides and sulphates), MSWI BA and FA are classified as hazardous waste (Zhang et al. 2019) and require careful treatment to reduce the potential leaching of contaminants into the landfill (Wang et al. 2019b). The heavy metals like Pb, Cd and Zn can be precipitated into the surface or leached into the groundwater if not properly treated. Typically, this occurrence can lead to soil and groundwater contamination, which has adverse impacts on the environment and human health (Wang et al. 2015). As the leaching of most heavy metals is highly dependent on pH, excessive addition of lime during the flue gas purification process could lead to higher alkalinity in the treated FA. This occurrence could promote the leaching of metals, especially Pb (Tong et al. 2019).

On the other hand, increasing concerns have been raised on persistent organic pollutants (POPs) in MSWI ash. The most common POPs include; polychlorinated dibenzo-*p*-dioxins (PCDDs), dibenzofurans (PCDFs) and biphenyls (PCB), which have carcinogenic, mutagenic and immunotoxic properties (Zhang et al. 2019). The PCDD/Fs are formed via two mechanisms. The first is the de novo synthesis, where heavy

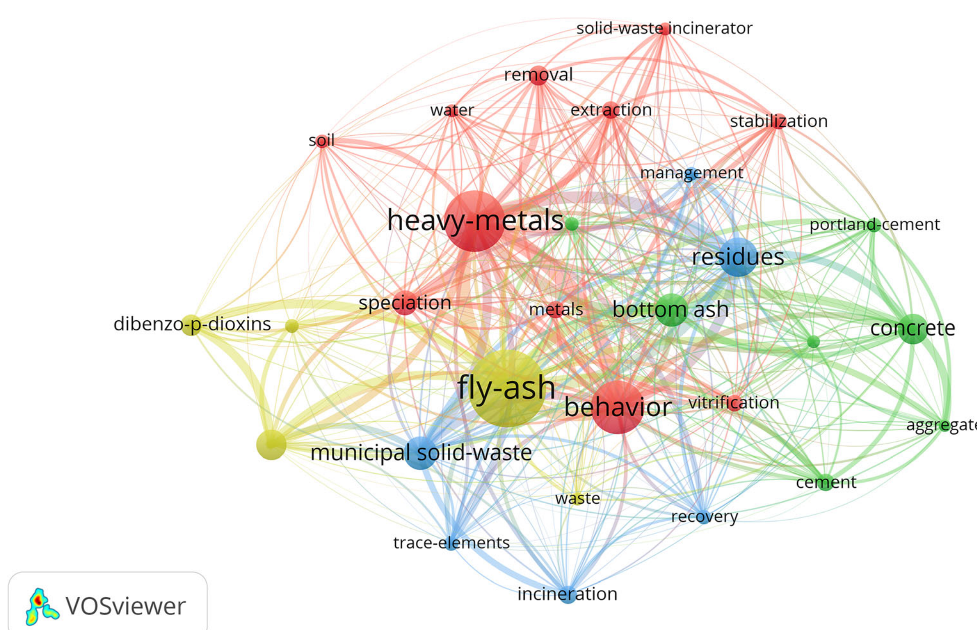

Fig. 7 Keyword analysis (minimum number of occurrence: 35, 50 out of 2108 keywords meet the threshold)

metals catalyse the formation of PCDD/Fs from residual carbons and chlorines at 250–450 °C. The second mechanism is the precursor synthesis, where chlorinated organic compounds are converted to dioxin via chlorination, condensation and oxidation (Xing et al. 2019).

MSWI has been recognised as one of the significant sources of anthropogenic POP emissions (Pham et al. 2019; Zhiliang et al. 2018). The persistent, ubiquitous and hydrophobic nature of dioxin-related compounds (DRCs) has increased their presence in the environment as well as human and animal fatty tissues. Human exposure to DRCs could lead to cancer, reproductive and developmental impacts. Other notable detrimental effects include endocrine disruption, immunotoxicity, neurotoxicity, organ toxicity and numerous transient acute health problems (Pham et al. 2019). Moreover, the incineration of MSW also causes the release of polycyclic aromatic hydrocarbons (PAHs). PAHs are a pervasive group of semi-volatile hydrocarbons, many of which exhibit carcinogenic, teratogenic and mutagenic properties. According to Peng et al. (2016), PAHs are primarily present in flue gas but fly ash contains more high-ring PAHs, such as the 3- and 4-ring PAHs that constitute the highest proportion of total PAHs. Thus, it is evident that the hazardous elements in MSWI ashes should be eliminated before landfilling to mitigate any negative impacts on the environment and society.

As mentioned in the "Utilisation of MSWI ashes (as a resource)" section 4.2.2, the conversion of MSWI ashes to value-added products is an important strategy to minimise the economic burden on landfill construction. However, the possible release of contaminants from the value-added products is a significant concern when considering such an option. In addition, chlorides reportedly impede calcium-silicate-hydrate gel formation in cement, while sulphates promote the formation of ettringite structures, which causes the extensive cracking of cement (Xuan et al. 2018a). Therefore, the excessive addition of FA as a binder in the cement could reduce the mechanical strength of the concrete formed (Dontriros et al. 2020). Chlorides also corrode the steel reinforcement in reinforced concrete, which accounts for over 40% of structural failures (Ramezanianpour and Riahi Dehkordi 2017). Given these findings, most scientific publications on this topic are related to detailed characterisations of the ashes. However, other studies examine the effects of various treatment methods on the composition of hazardous components in the ashes, as described by cluster 1 in Fig. 7.

Strategies developed for MSWI treatment

With the increasing popularity of incineration as an MSW management solution, proper management of MSWI ashes has become an important task to minimise the negative impacts on human health and the environment. Most of the earlier researches on MSWI ashes were performed to minimise the chemical hazards of the ashes for safe disposal in landfills. To fulfil this objective, many approaches have been developed over the years. Typically, these include (1) the removal of hazardous compounds from the ashes via washing, leaching and electrochemical treatment technologies; (2) the stabilisation of hazardous compounds in the ashes using various technologies (solidification, thermal and hydrothermal treatment as well as chemical stabilisation and mechanical processes), followed by the disposal of the final product in the landfills. Currently, these approaches are considered advanced for minimising the chemical hazards of the ashes.

The solidification/stabilisation (S/S) of MSWI ashes is another widely accepted technique, which satisfies the waste disposal law and environmental regulations in many countries (Joseph et al. 2018; Quina et al. 2018; Zhao et al. 2019). Nevertheless, an apparent paradigm shift (hence direction), which emphasises the resource recycling of MSWI ashes has been observed in the scientific literature. This change is in accordance with the concept of the circular economy, where the "cradle-to-cradle" principle has become increasingly important compared to the "cradle-to-grave" principle in waste management. The use of MSWI ashes as resources could significantly extend the lifespan of landfills while reducing materials consumption (and related environmental impacts) in manufacturing various products.

Nevertheless, the presence of MSWI ashes adversely impacts on the quality of products. Therefore, the main research focus on MSWI ashes is currently the optimisation of the percentage of ashes incorporated into cement or materials for road construction. Other areas include the analysis of mechanical strengths of the final products (concrete, mortar and road pavement). Lastly, the studies examine the minimum/acceptable impacts of MSWI to the environment based on the stipulated laws and regulations in different countries. These research elements are described by clusters 2, 3 and 4 in Fig. 7. The objectives of each approach and its related technologies are summarised in Fig. 8.

Critical analysis reveals that the documents retrieved from WoS mostly cover more than one cluster in Fig. 7, and most of the developed processes apply to FA and BA. Therefore, the "Removal of hazardous elements in MSWI ashes for safe landfill disposal (as waste)" and "Utilisation of MSWI ashes (as a resource)" sections present brief descriptions of Objectives 1 and 2, as depicted in Fig. 7. Furthermore, an overview of the specific techniques detailed in review papers is listed in Table 1. The analysis of recent literature also uncovered the emergence of new and innovative approaches in MSWI ashes management not presented in Fig. 7. The details of these innovative approaches, together with the challenges in the field, are highlighted in the "Innovative applications of MSWI ashes" section.

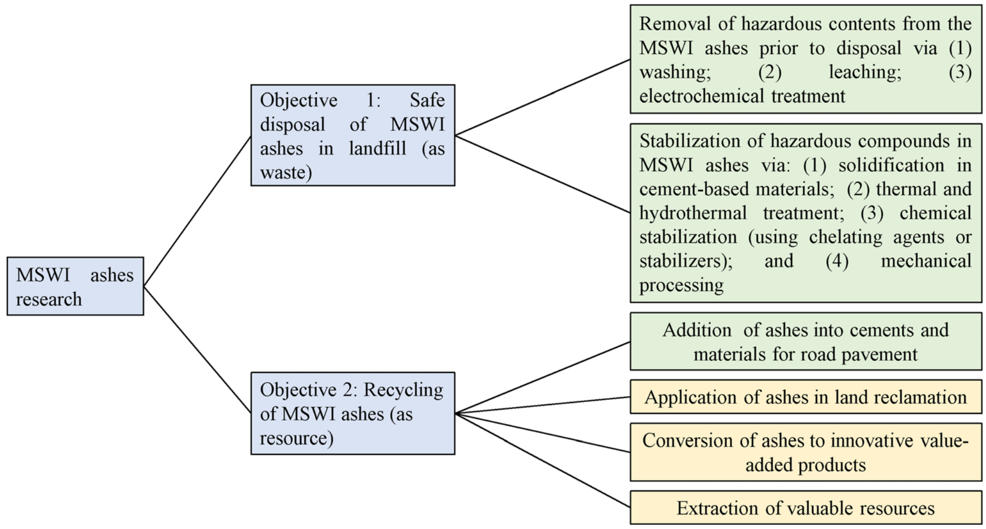

Fig. 8 Various objectives, approaches and technologies for MSWI ashes waste minimisation and valorisation. The text in the green boxes represents the advanced technologies, while the yellow boxes are the innovative applications of MSWI ashes recently developed by researchers

Removal of hazardous elements in MSWI ashes for safe landfill disposal (as waste)

Washing The presence of various PCDD/Fs, heavy metals, chlorides and sulphate contaminants in MSWI ashes is a threat to the environment and human well-being. Therefore, various technologies have been developed over the years to addresses this issue. Washing is perhaps the simplest process since the water-soluble pollutants can be easily removed by water (Margallo et al. 2015). The effectiveness of heavy metal removal through washing was also demonstrated on the MSWI FA from the Xinghuo waste incineration plant in Wuhan, China (Yakubu et al. 2018). The sample underwent a two-stage washing process using distilled water with liquid/solid (L/S) ratio of 10 for 15 min with stirring. The high heavy metals (Cr, Co, Ni, Cd, Cu, Zn) contents in the FA initially exceeded the USEPA method 1311 toxicity characteristic leaching procedure (TCLP) limit. However, almost complete elimination of chlorides and heavy metals was observed after the washing process (99.99% for Cd, 99.96% for Cu, 99.96% for Co, 99.95% for Zn, 98.61% for Cr, 98.12% for Ni). The leachate resulting from the washing process also meets the standard and can thus be safely discarded.

Wu et al. (2018a) investigated the potential use of the sulphate-rich biochemical effluent of landfill leachate (BEL) for the washing of MSWI FA. The BEL and FA were both collected from local landfills in Shanghai, China. The stirring of the BEL-FA mixture for 24 h produced similar dechlorination efficiency to re-distilled water (RW). In addition, the formation of calcium sulphate and hydroxides in FA after BEL washing could trap the heavy metals, which inhibits the leaching of Pb and Zn. The leaching concentrations of Pb, Zn, Cu, Ni and Cd of FA washed by BEL were found to be lower than RW. Moreover, the BEL washed FA has all the metal leaching concentrations that satisfy the Chinese national standards (GB5085.3–2007). The water washing step also effectively removed Na and K in the soluble chlorides.

Leaching Chemical leaching, which involves the detachment of soluble constituents from a solid phase by a solvent, is another popular method for the extraction of heavy metals from FA (Zacco et al. 2014). The extraction efficiency is influenced by the type of extraction solvent, pH and L/S ratio (Margallo et al. 2015). Weibel et al. (2018) recently demonstrated the effective immobilisation of heavy metals in MSWI FA using a two-step leaching process. The process utilised hydrochloric acid (HCl) (5%) and concentrated sodium chloride (NaCl) solution (300 g/L). Tang and Steenari (2016) showed that HCl is the most suitable leaching agent resulting in excellent leaching efficiencies for Cu, Zn, Pb and Cd. However, there are several downsides associated with the leaching method, including the use of reagents (generally not environmentally friendly) and the difficulty in the simultaneous recovery of multiple metals (Margallo et al. 2015). Water washing is less effective in sulphates removal from the MSWI ashes. However, washing with Na_2CO_3 or $NaHCO_3$ is a reportedly effective strategy for the process (Dontriros et al. 2020). Likewise, the desulphurisation of coal FA using $NaHCO_3$ has been a well-developed strategy in the last decade (Raclavska et al. 2010). The addition of $NaHCO_3$ in the extraction solution dissolves the sulphates in the form of $CaSO_4$, and the Na_2SO_4 formed is more soluble for easy removal (Dontriros et al. 2020).

Bioleaching is generally regarded as a greener option compared to leaching, as the former process requires lower cost and energy input (Funari et al. 2017). Typically, bioleaching refers to the production of organic and inorganic acids by microorganisms typically used to transform hazardous compounds into soluble and extractable forms (Xu and Ting 2009). The bioleaching of MSWI FA by *Aspergillus niger* was first proposed by Bosshard et al. (1996), who demonstrated the comparable leaching performance of microbially produced citric acid to commercial citric acid. The two-step process (fungi cultivation before leaching) is preferable to the one-step process (fungi incubation in FA) due to easier handling and optimisation. Wu and Ting (2006) investigated the efficiency of bioleaching (using *A. niger*) and chemical leaching (using various organic and inorganic acids) at different pulp densities of FA. Compared to chemical leaching, bioleaching displayed higher performance for manganese (Mn) and Zn leaching, comparable performance for Al leaching, and inferior performance for Cu leaching. Funari et al. (2017) showed that bioleaching using mixed sulphur- and iron-oxidising bacteria (which required only 0.810 L H_2SO_4) produced comparable removal performance for Al, Cu, magnesium (Mg), Mn and Zn when compared to chemical leaching (with 2.014 L H_2SO_4).

Electrochemical treatment Electrochemical treatment is another separation technology, which involves the reduction and oxidation reactions of the heavy metals (from MSWI ashes) on the surface of the electrodes due to a potential difference. It can be further classified into electro-dialytic and electro-kinetic treatment. The electro-dialytic treatment involves the use of ion-exchange membranes to restrict the movement of highly mobile heavy metals, whereas the latter does not. Zhang et al. (2017) employed the three-dimensional electrode method for the removal of heavy metals from MSWI FA in Chongqing, China. Apart from the stainless-steel cathode and graphite anode, graphite particles were added to increase the specific surface area of electrodes, which ensures a higher rate of mass transfer. The results showed that the removal rate for heavy metals gradually declined with the repair time. Furthermore, the repair time showed the most significant impact on the removal efficiency of heavy metals, followed by the voltage gradient and particle dose ratio. It was concluded that the configuration of 5% dosing ratio, 9-V voltage gradient and 5 days repair time provided the highest removal rate.

Yang et al. (2018a) employed an ultrasound transducer to activate the MSWI FA before the electrokinetic remediation (EKR). The results indicated that acoustic time in the sonification process has the greatest impact on heavy metals removal compared to controlling temperature and operating power. The maximum removal rate of Zn (69.84%), Cu (67.74%) and Cd (59.93%) were obtained at the acoustic time of 30 min, operating power of 120 W, and controlling the temperature at 45 °C. During the EKR process, a higher voltage gradient (2 V/cm) was observed to raise the removal efficiency of heavy metals. Although the electrochemical process does not require the use of chemicals, the treatment is not widely applied as it is energy-intensive and less efficient (Margallo et al. 2015).

Solidification/stabilisation Solidification in cement-based materials is another popular method for reducing the leaching of contaminants (mostly heavy metals) from hazardous wastes. Typically, these include; coal BA (Hashemi et al. 2019), smelting slag (Xia et al. 2019) and MSWI BA/FA in the landfills. This method generally involves the partial replacement of ordinary Portland cement (OPC) raw meal by pozzolanic waste materials. Although cement solidification is less effective in the stabilisation of soluble salts (especially Na and K in chloride form), the heavy metals in the MSWI ashes are effectively immobilised in the cement matrix. Typically, the process occurs through isomorphous replacement, complex precipitation, physical containment effect and adsorption (Fan et al. 2018; Yin et al. 2018b). However, the exact S/S mechanism is case-specific and closely related to the type of contaminants, selected cement matrix and external environmental factors (pH, humidity, temperature). Zhou et al. (2017) showed that ascorbic acid (2 wt%) could act as an effective stabiliser of the total chromium (Cr) and chromate (Cr (VI)) in FA. However, these chemical species could not be adequately stabilised by cementitious materials like other metals (Zn, Cd and Pb). The stabilised Cr species are then contained by the C-S-H and ettringite structures in their crystal structures. Sun et al. (2019) also developed a mixed chelator (containing sodium dihydrogen phosphate and piperazine dithiocarbamate), which was highly effective in the stabilisation of Cd (90.5%), Pb (96.2%), Cu and nickel (Ni) (both at 100%). According to the study, chelates with multiple chelating groups are more effective in stabilising heavy metals.

Mu et al. (2018a) showed that fishbone could be a natural source of hydroxyapatite (HAP) for S/S of heavy metals, especially Pb in MSWI FA. The stabilisation degree of Pb is positively correlated to the dosage of powdered fishbone and contact time. Nevertheless, the presence of a non-HAP fraction of the fishbone caused leaching of phosphorus (P) from the mixture, which aided the leaching of Cu and Zn from the FA. The ignition of fishbone effectively removed the non-HAP fraction, hence increasing the stabilisation efficiencies of Pb, Zn and Cu (Mu et al. 2018b). The ignition over 430 °C also converted HAP to low- and high crystalline structures that enhanced the stabilisation of Pb.

Most recent studies have focused on the role of chemical stabiliser in enhancing the S/S efficiencies of heavy metals. However, Wang et al. (2018) explored the effects of wet milling in stabilising the heavy metals in MSWI FA produced by a grate furnace incinerator (GFI) and fluidised bed incinerator (FBI). The treatment of the ashes in a planetary ball mill led to a smaller surface area with a rougher surface. In addition, it was observed that 24 h of milling was sufficient to reduce heavy metal leaching below the regulatory limit for both ashes. The observed reduction of heavy metals leaching from the ashes was due to the conversion of the elements from leachable to stable forms. However, a more significant stabilisation effect was observed for GFI ash, with over 90% leaching reduction for Cr, Cu, Zn, Pb after 24 h milling. The weaker stabilisation effect observed for FBI ash was possibly related to the content of the lower heavy metal than initially existed in the ash, as well as the presence of several elements.

Thermal and hydrothermal treatment Thermal treatment is another alternative for managing MSWI ashes. The treatment methods can be divided into three categories: vitrification, melting and sintering. Vitrification involves the addition of glass materials (and other wastes) to the ash to form a homogenous liquid phase and finally an amorphous single-phase glass. The melting process leads to different products, which consist of glassy materials and crystalline phases without the addition of glass materials. In the interim, the sintering treatment densifies the porous solid particles below the melting points of the components in the ashes (Gong et al. 2017a). An example of MSWI FA sintering was demonstrated by Gong et al. (2017a). In the study, the FA samples from Chengdu (China) were pressed at 20 MPa in cylindrical steel die with a dwell time of 1 min to obtain discs of 8 mm (diameter) × 2 mm (height). This was followed by sintering in the air at 700–1100 °C for 10 min before the natural cooling of the samples. After the thermal treatment at 1100 °C, the leaching concentration of Pb was reduced below the regulation limit for landfill disposal. However, the leaching concentrations of Cu and Zn declined only slightly but remained well under the limits. Even though the leaching toxicity of Cr increased, it did not violate the standard for landfilling. However, the authors noted significant inhibition towards the growth of *Escherichia coli* and *Staphylococcus aureus* in all the tested samples, possibly due to the bio-toxicity. Hence, the biocompatibility of products derived from MSWI FA requires careful inspection. Huber et al. (2018) proposed a combined disc pelletising and thermal treatment for MSWI FA. The FA samples were converted into pellets (~ 8 mm diameter) and heated in the rotary kiln at 450–1050 °C. The authors concluded that the operating conditions of 450 °C and 10 min were sufficient to convert the hazardous MSWI FA into a non-hazardous material. However, a minimum temperature of 650 °C was required to reduce the toxic equivalency (TEQ) of PCDD/Fs and dioxin-like polychlorinated biphenyls (DL-PCB). The high total dissolved solids in the final leachate indicated that an additional extraction process is required to convert the treated FA samples to non-hazardous waste before disposal.

Microwave-assisted thermal treatment is a popular method for the immobilisation of contaminants. According to a systematic study performed by Gong et al. (2017b), microwave heating is superior to conventional heating in terms of heavy metals (Pb, Cu and Zn) stabilisation. Nevertheless, the leaching of Cr increased after the thermal treatment due to the conversion from Cr (III) to Cr (VI), which is more leachable. It is also worth mentioning that the low evaporation of Pb (40%) at 700 °C can be further increased to 90% at 900 °C due to the decomposition of the chloride salts. In contrast, the vaporisation of Cr was lower than 20% at all temperatures tested.

Hydrothermal treatment is another waste treatment technology that involves the adsorption or containment of the heavy metals in the aluminosilicate minerals below the melting points (Margallo et al. 2015). Qiu et al. (2016) studied the potential of phosphate as an additive during microwave-assisted hydrothermal treatment. The effectiveness of different phosphate additives tested for heavy metals solidification was observed in the order of disodium phosphate (Na_2HPO_4) > monosodium phosphate (NaH_2PO_4) > phosphoric acid (H_3PO_4) > iron sulphate ($FeSO_4$). Similarly, Na_2HPO_4 showed the best performance for Cd stabilisation. The efficiency in the solidification of heavy metals improved at low L/S ratio, high temperature and higher additive dosage. The heavy metals content in treated FA satisfied the limits in GB16889–2008 with the optimum process conditions of 1.5 mol/kg for Na_2HPO_4, 2 mL/g for the L/S ratio, 10 min reaction time and temperature of 200 °C. As opposed to the conventional hydrothermal treatment, the authors concluded that the suggested approach saves more energy, time and cost. Shi et al. (2017) showed that the addition of silicon-aluminium source reduces the leaching toxicity of FA residues (after hydrothermal treatment) as well as the heavy metals content in the remaining liquid. This proves that heavy metals were indeed stabilised in the FA rather than leached into the liquid fraction. The silicon-aluminium additives were mainly required to adjust the ratio of Ca/ (Si + Al) so that tobermorite (aluminosilicate mineral zeolites) can be formed. Therefore, the authors recommended the addition of 30 mass% coal FA and a reaction temperature of 150 °C to be the operating parameters of hydrothermal treatment.

When coupled with microwave heating, hydrothermal treatment is perhaps the most promising method for PCDD/Fs destruction and heavy metals stabilisation, as demonstrated by Qiu et al. (2019a). In the study, the MSWI FA from the Hangzhou (China) incinerator plant experienced microwave-assisted hydrothermal treatment under different process conditions. The study aimed to reduce and estimate the total PCDD/Fs in the FA and the associated toxic equivalency of dioxins (WHO-TEQ). The most significant impact on the PCDD/Fs degradation, especially non-toxic dioxins was due to temperature. Furthermore, the findings showed that microwave-assisted hydrothermal treatment promotes the structural destruction and dechlorination of PCDDs.

Nevertheless, the microwave treatment also increased the molecular reactivity, which translates to the enhanced conversion of lower chlorinated PCDFs to higher chlorinated PCDFs. The water-washing of FA before the treatment could effectively reduce the chlorine content due to the likelihood of chlorination occurrence. With the addition of NaOH, the

PCDD/Fs destruction efficiency was increased to 83.7% (WHO-TEQ of 68.5%) at a process temperature of 220 °C and a processing time of 2 h. Further reduction in the PCDD/Fs content was achieved when Na_2HPO_4 was used. This observation was probably due to the extraction of chlorine from the PCDD/Fs coupled with the positive effects of Na^+ in dechlorination. Therefore, microwave-assisted hydrothermal treatment of MSWI FA (with Na_2HPO_4) after water-washing resulted in 91.8% reduction of PCDD/Fs contents and 90.2% reduction of WHO-TEQ value (Qiu et al. 2019b). Since Na_2HPO_4 effectively stabilises heavy metals in MSWI ashes, the treatment scheme is currently regarded as a sophisticated strategy to minimise the hazards related to PCDD/Fs and heavy metals in MSWI FA. More investigations are needed to provide further insights into the effectiveness of such treatment schemes on MSWI BA.

Utilisation of MSWI ashes (as a resource)

The technologies mentioned above ensure safe disposal of MSWI ashes in a landfill. However, the rising generation of the ashes requires the consumption of more resources and energy for the treatment of MSWI ashes. In addition, cement-based solidification of MSWI ashes, which is the most popular option for MSWI ashes treatment before disposal in a landfill, results in 1.2–2.0 times expansion of volume (Wang et al. 2017). Therefore, the technique is an unsustainable solution for addressing the rising generation of MSWI ashes in the long run. Following the introduction of the circular economy concept, scientists propose that MSWI ashes should be viewed as a resource that can be further utilised rather than as a waste. Thus, a significant number of studies have been dedicated to the conversion of MSWI ashes to various value-added products, as discussed in the following sub-sections.

Construction materials The use of coal fly ash and bottom ash, ground BFS and silica fume as supplementary cementitious materials (SCM) in cement production is an established disposal strategy due to the high contents of Ca, Al and Si (Dou et al. 2017; Meer and Nazir 2017). As MSWI FA and BA also share similarities in terms of their inorganic contents, the utilisation of these ashes as a partial replacement for OPC (ordinary Portland cement, a net primary CO_2 emission source) has become common practice. Thus, the applications of MSWI BA and FA as supplementary cementitious materials remain the most popular and widely studied recycling option for ashes (Biswal et al. 2019). The possibility of integrating cement production in a waste incineration plant was proposed by Ghouleh and Shao (2018) to fully utilise MSWI FA, waste lime, waste heat and carbon dioxide (CO_2) produced during the incineration process. The clinker containing FA (42.8 wt%), waste lime (42.8 wt%), hydrated lime (9.1 wt%) and silica sand (5.3 wt%) showed high CO_2 reactivity, as it consists of 51.2 vol% chloro-ellestadite. In addition, the FA required the least amount of virgin additives and lowest clinkering temperature as required for a typical waste incineration plant. Although the clinker showed less satisfactory strength increase upon hydration, carbonation for 2 h effectively increased the compressive strength to the reference ordinary Portland cement (OPC) upon hydration for 7 days.

Nevertheless, carbonation is required to activate the cement as the clinker exhibited less hydraulic property. Although higher Cr content was detected in the clinker compared to the precursor (most probably due to the decomposition of Cr-containing minerals during the heat treatment), such content is well below the regulatory limit. The practical stabilisation effect of the clinker is attributed to the thermal stabilisation, physical encapsulation (during carbonation) and densification of the resulting hardened matrix. Based on these results, the authors proposed the idea of implementing an in-situ clinker production unit within a local municipal incinerator. Such design enables closed-loop production of clean cement, where the heat and CO_2 generated during the waste incineration are used in the clinkering and carbonation of the clinker formed. A similar concept was also proposed by Diliberto et al. (2018), who suggested a zero-waste MSWI FA recycling route by combining clinker production with the extraction of chlorides and hydroxides (from the ashes washing water).

The application of MSWI ashes as SCM in the cement blend is also an interesting option to reduce OPC usage (Dou et al. 2017, Meer and Nazir 2017). This proposal is due to the high Ca, Si and Al contents that contribute to the high pozzolanic property of the ashes (Yang et al. 2018b). However, most studies have reported reductions in the compressive and flexural strengths of the cement composites with the ashes content due to the occurrence of alkali-aggregate reactions (AAR) reactions (Inglezakis et al. 2018). AAR refers to interactions between reactive compounds in the substitutes (silica, silicates, carbonates, etc.) with the alkali. Typically, these interactions result in the formation of products that lower the durability of the cement/concrete formed (Muller and Rubner 2006). For example, many research teams observed the production of hydrogen gas following the reactions of aluminium (Al) with moisture under alkaline conditions in the cement mix. The silica originating from the glass compounds can also dissolve in highly alkaline conditions to form alkali-silica reaction (ASR) gels. Lastly, the aluminium also reacts with sulphates to form ettringite. The evolution of hydrogen gas is known to cause porosities in the cement products, while the ASR gel can absorb moisture and swell. Hence, the reactions produce destructive effects in the cement structure and render the products useless. ASR reactions are accelerated at elevated temperatures (Xuan et al. 2018b).

There are currently two main strategies for addressing the ASR issue: minimising its occurrence by limiting the content of reactive silica/alkali/moisture in the cement mix. Secondly, by limiting the adverse effects of ASR on cement qualities using fibres/lithium or barium/air-entraining admixtures (Hay and Ostertag 2019). Nevertheless, recent studies have focused heavily on the first strategy, while the second strategy receives less attention. Xuan et al. (2018b) proposed the use of the dry-mixed method for preparation of mortar using MSWI BA with sizes below 3.5 mm. An adequate water/cement ratio of 0.30 was used for the dry-mixed sample. Upon comparison with a wet-mixed sample (water/cement ratio of 0.47), the cured dry-mixed mortar displayed higher flexural and compressive strengths. This is attributed to the porous nature in the latter that accommodates the H_2 gas and products from the ASR reactions and hence reduces the expansion of the mortar over time. The addition of SCM, primarily fly ash, into the dry-mix mortar could further reduce the ASR reactions related to the glass particles in MSWI BA. However, further studies are needed to validate the benefits of the dry-mixing method on cements made from MSWI BA and FA.

Zhu et al. (2018) proposed the use of alkaline treatment to remove the aluminium species in the BA before cement production. The treatment also leads to the immobilisation of certain metals (Fe, Mg, Ni, Se and Mo). However, the opposite trend was observed for Se and Mo. The concrete produced from alkaline treated MSWI BA showed higher compressive strength than the concrete from untreated BA, with the values of 34.7 MPa and 17.9 MPa, respectively, at the curing age of 28 days. At 90 days, the former concrete has strength comparable to the OPC (~ 53 MPa). However, the alkaline treatment of BA using $Ca(OH)_2$ is less effective compared to NaOH. This finding is probably due to the deposition of insoluble calcium aluminate on the aluminium surface, which impedes complete reaction. While treatment temperature seems to have negligible effects on the metal content of the concrete produced, the pozzolanic property of the treated BA reduces with alkalinity and temperature used during the treatment. Thus, it is essential to minimise the metallic aluminium content in the BA while maintaining the pozzolanic property.

By utilising the accelerated mortar bar test, Schafer et al. (2018) comprehensively examined the effects of alkali-silica reactions on the concrete properties when MSWI BA was used as an aggregate in Portland cement. Significant cracking was observed when the mortar materials contained over 30% BA, due to the formation of silica-rich gel and soda-lime glass. Nevertheless, the concrete expansion was not caused by the aluminium as expected by the research team. Instead, the reaction between the alkali hydroxides and the abundant silica in the BA is the main culprit for the expansion. Based on the testing results, a maximum of 15% BA could be used as SCM before deleterious concrete expansion occurs (according to ASTM C1260 and C1567 procedures) when Portland cement is the only binder used. Nevertheless, the addition of coal fly ash and ground glass as pozzolans can also effectively suppress the AAR, hence extending the lifespan of the concrete products even when higher BA content (30%) is used. The work demonstrates a new recycling method for waste glass, which could be a solution to waste management.

Hay and Ostertag (2019) present an interesting view on the importance of Al in reducing the ASR in concrete. The authors showed that the addition of Al compounds, even at small concentration, into in cement mix could effectively reduce the ASR. This finding is possibly due to the incorporation of aluminium into the silica framework, hence preventing its dissolution in highly alkaline conditions. In addition, Al reacts with silica to form $Al(OH)_4^-$, which covers the silica surface and repels other OH^- ions from further reactions with the silica. The hydrogen gas produced generates air voids in the concrete, which can accommodate the expansion of ASR gels without leading to concrete expansion. The Al powder is proven to be more suitable than bits and its dissolved form for preventing ASR. The powder reacts with OH^- ions in the alkaline environment to form $NaAl(OH)_4$, which readily dissolves to provide $Al(OH)_4^-$ ions that bind onto the silica framework. Since excessive hydrogen gas production could lead to the lower mechanical property of the concrete, the content of aluminium powder must be controlled or replaced with $Al(OH)_3$ to prevent H_2 production upon reaction with silica.

The presence of Al in a cement mix is undesirable. However, it could be useful in the production of certain construction materials, including the autoclaved aerated concrete (AAC). Luan et al. (2018) investigated the replacement of quartz sand by MSWI BA with different dosages and degree of fineness on the mechanical and leaching properties of the autoclaved aerated concrete (AAC). Its porous structure and low density typically characterise the material. This property is due to the reactions between Al powder and the silica in the quartz sand-cement mix that leads to hydrogen gas generation. Due to the high SiO_2 and Al_2O_3 content, MSWI BA serves as an economical silica source. However, BA also serves as an aluminium source for the gas foaming reactions simultaneously. Therefore, the effects of BA addition have to be observed with care. Investigations revealed that the hydrogen gas produced in the cement paste increased with the BA content (from 0% to 100%), while the opposite trend was observed at increasing BA fineness. This observation is due to the agglomeration of the fine powder in the cement paste, which reduced that effective reaction rate. Therefore, the bulk density and compressive strength of the AAC produced decreased with the BA content and increased with the BA fineness. The thermal conductivity of AAC also decreased with the BA dosage, due to the presence of porous structure. The characterisation results indicated that replacement of quartz sand by reactive SiO_2 in BA promotes the formation of tobermorite, which in turn increases the compressive strength of AAC.

Nevertheless, such positive effect is less significant compared to the adverse effect exerted by BA dosage. The team also observed the change of tobermorite structure with the BA content. The hydrothermal treatment in AAC production also effectively prevents the leaching of Cd, Pb, As, Zn and Cr, with ~ 100% efficiencies. The superior performance of AAC in immobilising the heavy metals in BA is supported by Biswal et al. (2019). The hydrothermal treatment successfully reduced the heavy metals leaching from the AAC, including Cu, As, Pb and Cr. Furthermore, a total of six metals, namely; Zn, Ba, Co, Ni, Ag and Cd were immobilised in the AAC. The authors attributed the observation to the immobilisation of heavy metals by tobermorite (formed during the AAC production) and inorganics (iron salts and phosphates). However, further studies are required to determine the exact mechanism involved in the processes(s).

Liu et al. (2018) developed an intermediate-calcium based cementitious material (ICCM) produced from MSWI FA. The ICCM is a cementitious material with a calcium oxide (CaO) content of 30–40%, and 0.75–0.90 for the ratio of $(CaO + MgO)/(SiO_2 + Al_2O_3)$. Typically, less energy is required for ICCM production, and it is easier to use than Portland cement. The compressive strength of the ICCM with MSWI FA percentage of 0–10% is higher than Portland cement, due to the presence of needle-shaped ettringite in the cementitious matrix. The ICCM is also useful in the solidification of heavy metals including; Pb, Cu and Cr, as evidenced by the leaching concentrations below the standard limit. Therefore, the production of ICCM serves as a practical and environmentally friendly solution for the management of MSWI FA and blast furnace slag (BFS).

Lightweight aggregates (LWA) are a class of construction materials with several exceptional properties, including low water absorption, high durability, adjustable thermal conductivity and lightweight (Giro-Paloma et al. 2019). The silicon oxide (SiO_2) and aluminium oxide (Al_2O_3) in BA, as well as metal oxides in FA, could serve as vitrification compounds and flux substances, respectively, for lightweight aggregate (LWA) production (Lam et al. 2010). Therefore, several research teams are currently investigating the prospects of diverting MSWI ashes towards LWA production. Chuang et al. (2018) studied the characteristics of LWA made from FA and BA from mechanical bed (MB) and fixed bed (FB) incinerators, together with reservoir sediment. In comparison, the FA and BA collected from MB incinerators possess higher CaO content. Therefore, the LWA produced from the MB residue exhibited higher water absorption rates (Chuang et al. 2018).

On the other hand, FB residues contained a higher percentage of SiO_2, which facilitates vitrification and reduced water absorption. The LWA produced from FB residues exhibited higher volume expansion (bloating) than variants from MB residues, with the highest bloating index observed at 1100 °C. The bloating occurs due to the capture of O_2 produced from the conversion of Fe_2O_3 to Fe_3O_4 inside the solid matrix. Besides, sintering of MB residues at high temperature (above 1100 °C) is required to produce LWA with high compressive strength, albeit with compromised bulk density. These observations show that ashes with higher SiO_2 and Fe_2O_3, together with lower CaO content are more advantageous in LWA production. Tang et al. (2019) showcased the possibility of recycling concrete slurry waste (CSW) and excellent BA through the production of the cold bonded lightweight aggregates (CBLAs). The study indicated the excellent compatibility of CSW and BA in the CBLA. Furthermore, the residual hydration behaviour of CSW contributed to the high mechanical strength of the product with minimum use of OPC or other binders. The leaching of tested heavy metals from the product also complied with the US Environmental Protection Agency.

Road construction In addition to the valorisation routes mentioned above, the MSWI BA is also suitable for utilisation as unbound, hydraulically-bound or bitumen-bound materials in road pavements applications (Lynn et al. 2017). Such applications have been widely adopted in Denmark, the Netherlands and Belgium, where diversion of MSWI ashes from the landfills are vital according to the circular economy concept. Likewise, research teams in other countries are investigating the potential of exploring such an alternative. For instance, Xie et al. (2016) showed that MSWI BA in China could be used as well-graded gravel or sand in road construction, provided the issue of heavy metals leaching is handled appropriately. The research team discovered the compressive strength reduction of the road base material following the partial replacement of limestone aggregates (due to the lower hardness of BA). However, the road base materials formed with 20 wt% of the aggregates replaced by the MSWI BA must meet the strength requirement for a heavy traffic highway in China. In another study, asphalt was shown to possess excellent immobilisation effects with MSWI FA (with leaching velocities of Zn, Cd and Ba in the magnitude of 10^{-6} cm/h). Nonetheless, the potential leaching of metals on the road surface by the acid rain requires further examination should such an alternative be adopted as an alternative in MSWI ashes management (Yang et al. 2018a).

The possibility of applying MSWI ashes in road construction in cold regions requires consideration of the freezing-thawing behaviour of the resultant materials. Typically, the occurrence of freeze-thaw is the main culprit of the deterioration of earthwork structures (Kamei et al. 2012). Tang et al. (2017) performed a detailed study on the effects of partial aggregates replacement by MSWI FA for road construction with an emphasis on the freezing-thawing cycle. The compressive strength of the cement formed decreased with the FA dosage, probably due to the dilution and destruction of hydration product structures upon the addition of ash. The addition of the chelating agent results in lower resistance of the cement towards freeze-thawing behaviour. However, the negative effect is outweighed by the superior heavy metal immobilisation effects. Therefore, it can be deduced that cement-chelated solidification is more environmentally friendly than cement-only solidification.

Innovative applications of MSWI ashes

Land reclamation Various innovative solutions have been proposed and demonstrated by research teams for the management of MSWI ashes. Typically, the novel technologies proposed aim to address local legislation requirements, challenges with existing applications, and the amount of MSW ash generated in different countries. For example, Singapore, as one of the densest countries in the world, has very limited land availability for its population. Therefore, the minimisation of wastes scheduled for landfill is of utmost importance. The idea of applying MSWI ashes in land reclamation is essential to close the waste loop while reducing the cost required to expand the land capacity of the country. A set of large-scale column trial experiments were performed by Yin et al. (2018a) to determine the leaching behaviour of heavy metals from MSWI BA into the seawater resulting from the land reclamation. Instantaneous heavy metal leaching into the seawater was reported during initial contact, with a uniform dispersion of heavy metals across the horizontal layer at all seawater depths. Nevertheless, higher concentrations were recorded at lower depths (where BA settled). The application of a chute for the dumping process reduces the total amount of heavy metals leaching. However, the higher concentration gradients across the seawater depth were also observed. The seawater depth exerts significant impacts on the heavy metals released from BA. As such, this parameter is proportional to the amount of time for BA contact with water, the degree of seawater disturbance due to BA settlement and re-suspension (Yin et al. 2019). Furthermore, the concentrations of certain heavy metals (Cu and Ba) decreased after the settlement of all IBA particles at the column bottom. This observation indicates the re-adsorption of these metals by BA, possibly due to the existence of the complexation surface. These reports convey similar metal leaching potential in the order: barium (Ba) > Cu > antimony (Sb) ≈ Cr > Ni > other metals, and provide essential insights into the environmental impacts caused by land reclamation using BA, and more studies are needed to validate such potential.

Another research team explored the metal leaching behaviour when using MSWI BA and marine clay (MC) for land reclamation in Singapore (Guo and Wu 2018). The BA and MC were chemically stabilised using a polymer-based stabilising agent, followed by mixing and dumping into a three-dimensional cell (as illustrated by Qing and Yu (2013)) for self-weight consolidation (SWC) and vacuum preloading (VP) processes. The use of the chemical-physical combination method (CPCM) successfully increased the shear strength of the IBA-MC matrix to ~30.0 kPa within 2 weeks. The measured strength significantly exceeds the requirement set by the Singapore government for land reclamation purpose. Low leaching behaviour was also observed for the 12 heavy metals in the effluents generated from the BA-MC mixture and BA-MC matrix.

However, the Cu contents in the samples from both sources (0.16 and 0.18 ppm) were slightly higher than the permissible limit for safe discharge into a watercourse in Singapore (0.1 ppm). This observation is possibly due to the binding of Cu to the dissolved organic carbon in the MC (Biswal et al. 2019). A simple coagulation process could reduce the Cu contents in the effluents to 0.06 ppm and 0.04 ppm, respectively, for the safe disposal of the effluents. In a tropical country like Singapore, contact of BA with rainwater during storage and transportation could be hardly avoided. Therefore, the team also studied the leaching behaviours of the metals in IBA into the rainwater for the 16 successive natural rain events. The concentrations of all elements were well below the permissible effluent discharge limits with exception to Cu. The research team concluded that BA-MC is a cost-effective and safe alternative to conventional landfilling materials, with only the minimum treatment for Cu removal from the effluent.

Landfill covers Disposal in landfill remains the most convenient disposal method for MSWI ashes, despite the extra costs involved in the process. Nevertheless, the release of contaminants from these ashes into the landfill is thought to be a burden for contamination control in the landfill. Yao et al. (2017a) challenged this view by proposing that MSWI BA positively influences the concentration of nitrogen compounds in the landfill. Their study involved the operation of a leachate re-circulated landfill bioreactor consisting of a BA layer (25 kg) placed in between two MSW layers (25 kg each) for 507 days. The authors also performed a weekly analysis of the nitrogen contaminants in the leachate produced at different locations of the reactor. The alkaline minerals in BA increased the pH of the leachate produced on top of the BA layer, which migrated downwards through the layer in the first 44 days. After day 44, the acid neutralisation potential of the BA gradually decreased. The minerals concurrently acted as adsorbents of the organic matter, which influenced the chemical oxygen demand (COD) of the leachate. Such property decreased gradually due to the occupation of the adsorption sites by pollutants. However, the pH and COD of the leachate collected at the bioreactor bottom were not affected by the MSWI BA layer at all times. The change in the properties greatly influenced the movement of nitrogen species in the bioreactor. Initially, the BA adsorbed the nitrates, nitrites and ammonia from the leachate. The adsorptive property gradually decreased, and then the nitrogen species started desorbing from the BA layer. Finally, an equilibrium was established, where the BA showed no significant effect on nitrogen migration. The team also observed the diverse leaching trends of Cu, Zn and Cr from the BA layer during the experiments (Yao et al. 2017b), due to the adsorption of the heavy metals by the MSW layer underneath the BA layer.

The potential of MSWI FA as adsorbents of hydrogen sulphite was also successfully demonstrated by Wu et al. (2018b). Double benefits could be derived from such an application. These include; the removal of H_2S generated in petrochemical industry or landfills, and the stabilisation of heavy metals by the S^{2-}. The two FA samples showed higher removal performance towards H_2S compared to coal fly ash and sandy soil. This finding is due to the H_2S adsorption onto the FA surface and pore walls and the subsequent metal sulphides formation. The metal oxides in FA could also promote the transformation of metal sulphides to sulphites and finally elemental sulphur. Considering the zero synthesis cost associated with the FA as absorbents, the high maximum adsorption capacities (29.15 mg/g and 24.27 mg/g, respectively) and the resultant S/S effect, MSWI FA could be used as landfill cover for the adsorption of H_2S in the landfills. These results indicate that BA could be used as a cover in landfills, as the MSW layer underneath could contain the contaminants released from the ash. Nevertheless, careful deliberation and strict control are required when considering the use of such ash as landfill liner.

Synthesis of silica compounds and glass-ceramic materials Although glass materials in MSWI BA could reduce the quality of the concrete, limited studies are dedicated to the treatment of such a component. Zhu et al. (2019) successfully converted the glass materials extracted from MWSI BA to binders with high strengths (up to 70 MPa). The alkali treatment resulted in high content of amorphous sodium silicate gel. The binder could be used as construction materials, and structural concretes provided that effective methods for the extraction of glass materials from MSWI BA are developed. Low-temperature synthesis of sodium silicate and ordered mesoporous silica from MSWI BA for high-end applications was successfully developed by Alam et al. (2019). Nevertheless, the effects of the contaminants in BA on the products have to be investigated to determine the viability of the process. Romero et al. (2018) investigated the transformation of vitrified BA into cellular glass-ceramics through mechanical foaming of alkali-activated suspensions of waste glass powders, followed by sinter-crystallisation at 800–900 °C. The resulting foams possessed excellent compressive strength (> 6 MPa) with an overall porosity of 80%, and the detailed investigations on the potential of such technology are on-going.

Compared to the applications above, the synthesis of ceramic-based materials from MSWI ashes have received more attention from several research teams. This is due to the exceptional properties of these materials; high thermochemical resistance, high durability and hardness, together with low electrical and thermal conductivity. Furthermore, the high temperatures used during manufacturing effectively destroy organic contaminants, especially dioxins. Therefore, various ceramic-based materials, including; general ceramics, glass-ceramic foams, bricks and tiles, are developed from MSWI ashes. The study by Silva et al. (2017) provides a detailed analysis of the developments in this area.

Recently, different materials with unique compositions and applications have been developed and tested. These include; zirconium-rich alkaline-resistance glass (Mbemba et al. 2019), and glass-ceramic foams from MSWI BA and FA (Liu et al. 2019a). However, the high processing costs due to the high temperatures used during thermal treatment (typically 1400 °C for vitrification) limits the wide-scale adoption of such a technology. Ponsot et al. (2015) demonstrated successful glass-ceramics synthesis via sintering of MSWI FA at 1050 °C. The process enhanced the satisfactory chemical stabilisation of FA, as confirmed by the leaching studies and cell culture tests.

Romero et al. (2018) also developed an "inorganic-gel casting" method for the synthesis of glass-ceramics foams at 800–900 °C. The findings showed that the presence of boro-aluminosilicate glass could further lower the processing temperature to 800 °C without compromising the substantial metal stabilisation. The synthesised glass-ceramics, which is rich in iron oxide, can be used to shield humans from electromagnetic exposure while minimising electromagnetic interferences.

Synthesis of adsorbents for wastewater treatment and gas purification Luo et al. (2017) demonstrated another potential application of MSWI BA: conversion to porous adsorbents. The study involved mixing BA samples (< 300 μm) with sodium hydroxide (NaOH), followed by treatment at 150 °C and 1.6 MPa for 18 h. This process converted the compact solid structure of the raw BA particles to a porous microstructure. The highly alkaline conditions during treatment also promoted the formation of new crystal phases. The process occurred through the dissolution of SiO_2 and Al compounds followed by re-precipitation with Ca minerals to form a product comprising zeolite, katoite and gehlenite. The product possessed high surface area (129.98 m^2/g) with meso- and micro-porous structures. The negative charge detected on the material surface was related to the presence of aluminate and silicate groups. The hydrothermal treatment process significantly reduced the leaching of Cr, Ni, Cu, Zn, arsenic (As), Cd and Pb.

The satisfactory adsorption performance of the hydrothermally treated IBA towards 3-chloroaniline and triclosan (emerging contaminants used in pesticides, pharmaceuticals and personal care products) were also reported (with the maximum adsorption capacities of 62.43 mg/g and 42.37 mg/g, respectively).

The same research team also studied the role of humic acid (HA) in hydrothermal treatment of MSWI BA (Luo et al. 2019). Based on the morphological and spectroscopic characterisation results, HA participated in the complexation of metal ions in BA during hydrothermal treatment. The treated product consisted mainly of torbernite, with smaller surface area (26.9 m^2/g) together with meso- and micro-porosities. The efficient performance of the synthesised adsorbent towards Cu (II) ions was also observed, with a maximum adsorption capacity of 270.27 mg/g. Therefore, the MSWI BA treated with HA serves as a promising sorbent for the removal of Cu from wastewater. This study also reveals the potential of hydrothermal treatment as a solution for Cu leaching from MSWI BA, as mentioned by Guo and Wu (2018) who considered its application as a landfill liner. Instead of releasing Cu into the environment, hydrothermally treated MSWI BA could adsorb the Cu released by the MSWI BA layer used as landfill cover.

Qiu et al. (2018) showed that the introduction of microwave heating reduces the time needed for adsorbent production from MSWI FA via hydrothermal treatment. The adsorbent (with structure similar to zeolite) possesses a BET surface area of 40.12 m^2/g and demonstrated high adsorption performance towards Cu (adsorption capacity: 32.05 mg/g) as well as mixed heavy metal cations (Cd, Cu, Mn, Ni, Pb and Zn, total adsorption capacity: 101 mg/g). Wang et al. (2016) showed that the large surface area and low Si content in MSWI BA with smaller particle size contributed to higher removal efficiencies of organic dyes and heavy metals compared to BA with the larger size. These studies demonstrate the potential of MSWI ashes as a waste-derived precursor of adsorbents, in addition to biomass waste (Arshad et al. 2019) and industry waste (Wong et al. 2017).

Electrode application in MFC The electrochemical activity between yeast and an electrode was first reported in the early twentieth century. However, Habermann and Pommer (1991) constructed the first microbial fuel cell (MFC) that utilised bacterial to produce electricity from municipal wastewater. Today, MFC is regarded as a potential solution to electricity generation and wastewater treatment, especially in remote areas and developing countries (Slate et al. 2019). Nevertheless, the high cost of electrode material (platinum) hampers the development of MFC technology. Webster et al. (2018) proposed the application of MSWI ashes as a potential low-cost MFC electrode. The application of electrode potential (50–125 V) to the ashes in deionised waster successfully lowers the melting point, while increasing the hydrophilic property. It is hypothesised that the process reduces the metal oxides in the ashes to pure metal (as evidenced by the change of ash colour and morphology), leading to increased conductivity. The use of such a low-cost fuel cell electrode could improve the economic viability of MFC for wastewater treatment, electricity generation, and address many of the Sustainable Development Goals (SDG).

Clean hydrogen production The reaction between the inherent aluminium in the MSWI ashes, as well as new aluminium with water under alkaline conditions, could be a new alternative to hydrogen gas production from natural gas reforming and water electrolysis according to Nithiya et al. (2018). Analysis of the MSWI BA collected in Japan revealed the existence of metal Al aggregates, and the high alkalinity in BA ($pH > 12$) favours Al dissolution in water via partial anodic reaction. The electrons released during such reaction could trigger a partial cathodic reaction, which resulted in the formation of H_2 gas and hydroxide ions. The increased solution pH after the reaction could trigger the dissolution of more Al, accompanied by H_2 generation (Saffarzadeh et al. 2016). Such a process can be applied on MSWI ashes as pre-treatment before recycling. Furthermore, the hydrogen gas collected in the process could be used in fuel cell applications, whereas the treated ashes could be used in concrete production with minimum adverse effects from Al. However, more detailed investigations on such process are needed to facilitate further understanding and enhance process design and optimisation.

Urban mining Following the development of electronic gadgets and machinery, various precious metals, especially gold (Au), silver (Ag) and rare earth metals have been widely used in the production of printed circuit boards and batteries. However, the extraction of these metals from natural ores is often costly, resource-consuming, and detrimental to the environment. On the other hand, improper treatment of waste electric and electronic equipment (WEEE) often leads to an accumulation of these valuable metals in the MSW. Due to the high exploitation value of these metals in WEEE, "urban mining", defined as reclamation of compounds and elements from anthropogenic stocks (Cossu and Williams 2015), has become an essential alternative to traditional mining. Tang et al. (2018b) proposed that MSWI ashes could also be viewed as new urban mines of valuable metals, including Zn, Cu, in addition to many other metals, especially when WEEE pre-treatment before incineration is absent. A method for Zn recovery using Cyanex 272, developed by Schlumberger et al. (2007) is capable of recovering 48 kg of Zn per tonne of filtered ash. Tang and Steenari (2015) evaluated an approach to recover Cu and Zn sequentially from MSWI FA via HCl leaching.

Consequently, the Cu is extracted from the acid leachate using LIX860N-I, and finally, Cyanex 923 was used for Zn extraction from the Cu-depleted aqueous phase. Selective extraction of Cu and co-extraction of Zn with other metals were observed. The co-extraction issue could be tackled by using a suitable extractant. Tang et al. (2018b) employed a novel commercial extractant, Cyanex 572 to selectively extract Zn from ash leachate. Cyanex 572 demonstrated a higher selectivity and yield for Zn with 91% recovery of Zn compared to 76% recovery by Cyanex 923.

Moreover, Cyanex 572 was more advantageous with lower acid consumption and higher stripping efficiency. Tang et al. (2018a) also investigated a hydrometallurgical process developed for Cu and Zn recovery at pilot scale (close to industrial scale) and the landfill compliance of ash residue after the process. LIX860N-I and Cyanex 572 show high Cu and Zn selectivities, with 95% and 61% yields, respectively. Compliance leaching test showed that the residue satisfied the criteria for landfilling of non-hazardous waste. The authors suggested that the combination of metal recovery and landfill disposal of ash residue could be the most effective technical and economic strategy.

Economic and supporting policies for MSWI ash management

The development of MSW recycling technologies is mainly driven by profits from the sale of the values-added products, which could alleviate the economic burden (especially tipping fees) faced by operators during the landfilling of solidified MSWI ashes. In addition, the replacement of natural resources with MSWI ashes in industrial processes also dramatically reduces the material costs, provided the impurities present in the ashes does not affect the process or the product quality. While most research works on MSWI ashes research determine the technical feasibility of various possible technologies, only a handful of studies are dedicated to the economic feasibility of these technologies. Based on a life cycle assessment, Huang et al. (2017) explored the economic benefits and environmental impacts of recycling of MSWI FA generated in Taipei (Taiwan) through different technologies. Compared to the disposal of stabilised/solidified FA in a landfill, the reuse of the water-washed ash in brick production (10 wt.%) leads to 64.3% cost reduction. Likewise, the reuse of the water-washed ash in cement production (20 wt.%) reduced the treatment cost further to 86.3%. The authors also proposed the use of water-washed FA as a replacement for limestone in the Waelz process (for zinc oxide recovery from the electric arc furnace ash), which could reduce the treatment cost by 63.9%. Sarmiento et al. (2019) estimated the cost-saving of US$ 0.04–1.8 per ton of clinker (5 wt.% replacement by MSWI ashes) produced in Florida, United States. The 5% replacement of clinker raw materials could reduce 37.5% of the MSWI ashes generated in Florida that ends up in landfills. The fluctuation in the cost-saving is mainly attributed to the different chemical compositions of the ashes (which in turn affect their percentages in the cement raw mix) as well as the distance of the MSW incinerators to the cement kilns (which influence the transport costs). Golestani et al. (2017) presented an interesting analysis of the use of MSWI BA and recycled asphalt shingle in pavement construction. While the incorporation of BA into the hot mix asphalt is considered a plausible solution, higher optimum binder content is necessary. This condition is due to the absorption property exhibited by BA particles, which reduces the performance of original asphalt. In addition, the incorporation of recycled asphalt binder is considered a practical solution to the issue. Hence, the incorporation of BA (20%) and recycled asphalt binder (5%) reduces the overall net costs for the construction and maintenance by 46%. Another analysis of the economic benefits of MSWI BA recycling in cement production in Macao (China) was performed by Sou et al. (2016). Compared to the other options (including burial, construction, and demolition waste, along with 25% replacement of natural aggregates in cement concrete, and 25% replacement of natural aggregates in asphalt concrete), the replacement of cement by pre-treated BA (25%) produced the most economic benefits. The latter option also serves as the best solution considering the environmental impacts and health risks, together with social and legal implications.

Prospects and challenges in MSWI ashes research

Despite the fast progress in MSWI research, several challenges that limit the progress in MSWI ashes research are identified in the literature. These include the absence of well-developed, robust and economical characterisation methods for the precise quantification of PCDD/Fs present in the MSWI ashes. This observation limits extensive research on the removal of the contaminants from the ashes. Therefore, it is necessary to divert more resources to the development of reliable characterisation methods, and the development of various empirical-based strategies for tackling environmental pollution by PCDD/Fs in MSWI ashes. Furthermore, it is necessary to identify the threats posed by chemical species in MSWI ashes, which have been overlooked previously. For example, magnetites (in pure, impure and intermediate forms) in the MSWI ashes are the leading magnetic carriers (with superparamagnetic behaviour) that compromise the use of the magnetic properties of ashes for practical purposes. Typically, the superparamagnetic particulates (SP) component consists of 16–22% in BA and 25–31% in FA samples according to the conservative estimation by Funari et al. (2018). Therefore, more studies are required to determine the health hazards of nanosised SP accidentally released into the atmosphere and sophisticated mechanisms to contain such pollutants.

Despite the rapid progress in MSWI ashes research, various experts, governments and the public still possess mixed views on the application of MSWI ashes as construction materials, especially when considering environmental sustainability. The material flow analysis performed by an Austrian research team (Holm and Simon 2017) showed that the incorporation of MSWI FA into the Portland clinker production increases the total raw material input by 0.9%. However, a significant increase in the heavy metals content in the cement was produced (Cd 310%, Pb 170%, Hg 90%, Zn 70%, Cu 20%). It is also worthy to note that As and Cd contents in the concrete are only slightly lower than the limit values established by the Austrian ordinance for recycling construction materials. Therefore, the authors concluded that it is impossible to increase the MSWI FA input from 0.9 to 22% (as suggested by other research teams) without exceeding the mentioned limits. The team also raised concerns on the effects of the total heavy metals contents on the recycling of demolished concrete.

Numerous studies have demonstrated the technical feasibility and economic benefits of various MSWI ashes recycling technologies. However, the supporting policies in different countries play essential roles in the implementation of these technologies in the ash treatment industry. The comparative analysis of Liu et al. (2015) showed that the existence of national policy framework on MSWI ashes recycling is mainly driven by sizeable total population (China) or high population density with limited land availability (Japan, South Korea, Singapore, Taiwan). In addition, the study stated that the environmental regulatory performance of the country is a critical dynamic. In particular, environmental regulation is paramount in the European Union (EU), which aims to minimise waste generation and maximise the use of waste as resources. While the waste acceptance criteria (WAC) is established in Europe for the incorporation of MSWI residue in construction applications, the setting of the WAC criteria in the member states is mainly dependent on various factors. Typically, these dynamics include; the history in national solid waste management regulations, economic impacts, and the associated environmental impacts. The influence of the environment is particularly evident when considering the importance of groundwater (which is susceptible to improper MSWI ashes management) as a drinking water source. Taiwan is the first Asian country to apply the cradle-to-cradle concept in designing a resource circulation and reuse strategy (Pariatamby and Tanaka 2014) based on the widespread use of MSWI BA in construction.

On the other hand, China, which has become the largest MSW generator in the world, has no relevant policy available related to re-utilisation of MSWI ashes in the country. Instead, the country has preferentially opted for incineration over landfilling. Hence, the BA generated is directly landfilled (according to the Standard for Pollution Control on the Landfill Site of Municipal Solid Waste). Alternatively, the BA is used in cement kilns (according to the Standard for Pollution Control on Co-processing of Solid Waste in Cement Kilns) provided that lower heavy metals leachability is demonstrated. Although MSWI FA is treated as hazardous waste, landfilling and treatment in cement kilns are allowed if specific regulatory requirements are fulfilled. The lack of supervision and regulatory enforcement on FA treatment and disposal has prohibited recycling resulting in increased heavy metals concentration in the terrestrial environment surrounding the MSW incinerators in China (Ma et al. 2018). It stands to reason that MSWI FA will soon become another significant heavy metal pollution source if no actions are taken. To prevent such an outcome, regulatory enforcement and enhanced supervision are required. In addition, financial incentives are required by the government to support the development of MSWI FA recycling technologies (Wang et al. 2019a).

Despite the wide adoption of MSWI in the USA, the recycling of the resultant ashes (estimated at 6.6 million tonnes in 2010 (Oehmig et al. 2015)) is nearly non-existent. This is ascribed to the lack of policy framework to support such an initiative. Following the EzBase controversy in Florida (Hollett 2017), the public is concerned about the potential effects and lack of institutional control on the recycling and reuse of ashes in road pavements construction. In addition, there are growing concerns about environmental contamination and the health impacts of MSWI ashes on local communities, thus hampering efforts on recycling. The policy analysis study by Clavier et al. (2019) revealed the shortcomings and consequences of using TLCP on MSWI ashes to the MSWI operators in the USA. Published in 1990, the TCLP was designed to determine the contaminants leaching from the waste materials (including MSWI ashes) in a landfill under a worst-case scenario. While BA is generally non-hazardous, FA, which is rich in heavy metals, can quickly fail the TCLP test. Thus, the FA is treated as hazardous waste according to the Resource Conservation and Recovery Act. Furthermore, operator experience and tests results show that Cd and Pb are the most hazardous elements in FA during a TCLP test. It is argued that while conditions used in TCLP does not represent real disposal conditions in most cases, the accuracy of leaching results derived from the procedure can be easily affected by operator errors (Liu et al. 2019b) (assumed to be unintentional). Thus, the test does not provide a conservative estimate of the leaching potential (Intrakamhaeng et al. 2019).

Given the sizeable MSWI FA generated at incineration facilities, operators often tend to commingle the FA with BA to produce a non-hazardous waste (according to the TCLP leaching standard). The process also helps operators avoid the management of FA as hazardous waste, which is extremely costly. This mixing is also performed to reduce the Pb content in the commingled waste (CA) below the TCLP limit while maintaining the pH of CA (between 9 and 10) to avoid failing TCLP for Pb and Cd. The introduction of additional lime (beyond stoichiometric ratio) into the air pollution control device is another strategy to maintain the CA within the desired pH range. Such schemes successfully produce a CA that is non-hazardous, although at additional costs due to lime utilisation. Furthermore, the recovery of scrap metals from the CA has proven more difficult due to the presence of lime and fine particles from FA, while the possibility to recycle BA also diminishes. The disposal of highly alkaline CA in monofills could also possibly lead to elevated Pd leaching. In a nutshell, the high treatment cost for hazardous waste coupled with the nature of TCLP (which often fails to simulate most actual ash treatment conditions in the industry) motivates the MSW incineration operators' to focus solely on passing the TCLP, thus neglecting the potentials of ash recycling in the US. In addition, the treated CA could possibly be more hazardous under certain disposal conditions. To rectify this scenario, scholars urge for the design of a policy framework backed by a more appropriate characterisation protocol. For example, the Leaching Environmental Assessment Framework (LEAF), which allows the shift of operators to focus on technologies for ashes recycling. In addition, the improvement of existing ash reuse policy in US should be performed with the focus on ash segregation, engineering controls and institutional controls (Oehmig et al. 2015). More insights from the experts in this field are required to address these issues and gain the acceptance of governments in different countries, which is vital for the effective recycling of MSWI ashes. Perhaps, the ultimate solution to the MSWI ashes management is the responsible consumption and production of consumer products, as stipulated in the Sustainable Development Goals (SDG) initiative.

Limitation of this study

The accuracy of the bibliometric analysis in this study is limited to the percentage of total scientific publications retrieved from the WoS database related to MSWI ashes research. The search string was designed to retrieve all the related scientific documents indexed by WoS. However, it is impossible to determine the number of documents that fulfilled the search criteria but not retrieved by the search string. The authors also noticed that WoS might preferably index articles and journals written in the English language. Therefore, it is possible that a large number of influential articles/journals that are produced in other languages, particularly Mandarin (in the view of the fast progression of the research status in China), are not indexed in WoS. The authors believe that the bibliometric analysis based on output from WoS is sufficient to illustrate the development of MSWI ashes research. However, a similar analysis based on outputs from the Chinese National Knowledge Infrastructure (CNKI), Google Scholar, Scopus and Pubmed databases would be beneficial.

Conclusion

This paper presents the global research trends on MSWI ashes based on articles and conference proceedings published from 1994 to 2018. The analysis result based on the 1810 documents retrieved from the WoS Core Collection revealed the rapid progress of MSWI ashes research in the studied period. Such development was mainly related to the availability of funding from the China agencies and the international collaboration between China and other European countries. China produced the highest number of documents on MSWI ashes research, followed by Japan, Taiwan and Italy. Waste Management, Journal of Hazardous Materials, Chemosphere, and Waste Management & Research are identified as the core journals for MSWI ashes research. Five organisations in China are listed in the top ten productive organisations, while the Technical University of Denmark and KU Leuven produced higher impacts in the field as evidenced by higher citation/document. Based on the keyword co-occurrence map, the current emphases of MSWI ashes research include detailed characterisation of the ashes, dioxin emissions from FA, BA valorisation technologies and heavy metals removal from the ashes. As such, numerous strategies have been developed to reduce the negative impacts of MSWI ashes on the environment. These include stabilisation or removal of hazardous components in the ashes using various technologies before landfill disposal and ashes utilisation in the construction sector (which lead to a reduction of natural resources consumption in the production of construction materials). Other notable strategies include the production of value-added products from the ashes and utilisation of the ashes for various applications. The improvement of PCDD/Fs characterisation methods and careful examination of previously unnoticed contaminants in MSWI ashes are among several future directions on MSWI ashes research. Nevertheless, the reduction of MSW generation through responsible consumption and production, along with the recovery of recyclable wastes are potential solutions to the management of MSWI ashes. Hence, this paper provides researchers with an overview of publication trends, productive countries, organisations, and authors along with the associated collaboration networks, and recent development in the MWSI ashes treatment technologies. Likewise, it presents an overview of the many technologies and applications of MSWI ashes treatment, which could be useful to industry players and stakeholders. As the analysis reported in this study was solely based on the output from WoS, similar analysis based on data extracted from other databases, especially Chinese National Knowledge Infrastructure, will help validate the findings described in this study.

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