Environmental Sustainability from Waste to Resource: A Bibliometric Analysis of Municipal Solid Waste Incinerated Bottom Ash Research

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Abstract
Municipal solid waste (MSW) generation has risen steadily with higher incomes, rapid urban growth and economic activity, and is expected to reach about 3.4 billion tonnes a year by 2050. Waste-to-energy (WtE) incineration is now widely used to cut waste volume and recover energy, and India has been adding such plants under programmes like the Clean India Mission. The bottom ash left after incineration makes up roughly 80 to 90 percent of the residue. Reusing it also supports several Sustainable Development Goals, mainly SDG 11, 12 and 13, by saving natural aggregates and reducing the land needed for disposal. This paper reviews global research on MSW incinerated bottom ash (MSWIBA or MIBA) using a bibliometric approach based on the Web of Science Core Collection (SCI and SCI-E). After the export was cleaned of unrelated records from 110 to screened 69 papers published between 2004 and 2023 were analysed in Microsoft Excel and VOSviewer. We examined document type, yearly output, subject area, source journals, publishers, authors, language, keywords, citations and contributing countries. The 69 papers received 1065 citations in total (about 15.4 per paper; corpus h-index 19), and output rose sharply after 2020. China leads the field, followed by a group of European countries together with India and Taiwan, and Construction and Building Materials is the most active journal. The keyword data show the focus moving over time from heavy-metal leaching and basic characterisation towards reuse, geopolymerisation and supplementary cementitious applications. A short thematic review of the wider literature is added to place these numbers in context.

Keywords: bibliometric analysis; municipal solid waste incinerated bottom ash; MSWIBA; waste valorisation; circular economy

1. Introduction

1.1. General

Higher living standards, a growing economy and fast urbanisation have together pushed municipal solid waste (MSW) generation to its highest levels yet. Both developed and developing countries now find it hard to manage and safely dispose of the waste they produce. Landfilling remains common, but incineration, and waste-to-energy (WtE) plants in particular, has gained ground as one answer to the problem. Incineration can cut waste volume by about 90 percent and mass by roughly 70 percent while recovering energy (Kumar and Singh, 2021; Chen et al., 2023). In India, MSW incineration is being taken up under national programmes such as the Clean India Mission, and several plants are already running with more planned.

The global figures behind this shift are striking. In the 27 European Union countries, the share of MSW sent to incineration rose from about 15 percent in 1995 to roughly 27 percent in 2020. In the United States, energy-recovery combustion grew from almost nothing in 1960 to about 12 percent by 2018. In China, the incinerated share climbed from around 3 percent in 2004 to about 62 percent (some 146 million tonnes) in 2020. India followed a similar path, with installed WtE capacity increasing from about 53 MW in 2009 to roughly 217 MW in 2021 (Chen et al., 2023).

Burning MSW, usually between 850 and 1000 degrees Celsius, leaves solid and gaseous residues. Of the solids, bottom ash (BA) is by far the larger share, about 80 to 90 percent of the residue, while fly ash (FA) is a smaller and more contaminated stream that is normally treated as hazardous. Bottom ash is generally taken to be non-hazardous. It is rich in silica and calcium and behaves like a coarse aggregate, so it can stand in for natural raw materials in road works, building materials, landfill cover and various geotechnical uses (Lynn et al., 2017; Cho et al., 2020).

Per-capita waste generation in India has climbed over the past few decades, putting pressure on collection, treatment and disposal. Where disposal sites are poorly run, the emissions and leachate they release can harm public health and the environment. For these reasons solid waste management is now treated as a development priority, and it ties directly into several of the United Nations Sustainable Development Goals, namely SDG 11 (sustainable cities and communities), SDG 12 (responsible consumption and production) and SDG 13 (climate action). With sand mining under growing restriction and demand for construction aggregates rising, recycling bottom ash as a substitute would ease the demand on natural resources and cut the land taken up by residue disposal (Blasenbauer et al., 2020; Verbinnen et al., 2017).

Incinerated municipal solid waste bottom ash, written variously as MSWIBA, IMSWBA or MIBA, can replace conventional raw materials in cement and concrete, road base and subgrade, lightweight aggregates and landfill cover. Researchers have also tried it in alkali-activated and geopolymer binders, glass-ceramics, adsorbents and even hydrogen production (Kumar and Singh, 2021; Dou et al., 2017). How it performs depends a good deal on the feed waste, the furnace, the temperature, the residence time and the way the ash is quenched, so chemical characterisation and some pre-treatments are needed before it can be reused safely and within standards. Even so, the evidence base is uneven across regions, and in practice much of the ash is still dumped or landfilled. A structured look at the literature is therefore useful to see what is known, who the main contributors are, and where the field is heading.

1.2. Research Focus

Bibliometric analysis is a quantitative way of reviewing a body of work. It identifies the core papers, authors and institutions and the links between them, and helps connect research with practice. A narrative review struggles to summarise a large literature without bias, whereas bibliometric and network methods bring out the structure and the trends. An earlier bibliometric study of MSW incineration ashes covering 1994 to 2018 (Wong et al., 2020) showed the value of the approach. The present work updates it and narrows the scope to bottom ash, with the aim of giving researchers a clear picture of the influential work, the productive groups and the rising themes in the reuse of incineration residues.

2. Procedure of Analysis

The study used the Web of Science (WoS) Core Collection. The Science Citation Index (SCI) and the Science Citation Index Expanded (SCI-E) were taken as the object databases, and the search was run on the topic field (TS) with the query below:

TS = (("MSW INCINERATED BOTTOM ASH") OR ("MSWIBA") OR ("MUNICIPAL SOLID WASTE INCINERATED BOTTOM ASH") OR ("MIBA") OR ("MUNICIPAL SOLID WASTE INCINERATED ASH"))

Records were exported as a tab-delimited file with their full bibliographic fields. The acronym "MIBA" and the phrase "incinerated ash" also turn up in unrelated fields such as microbiology databases, chemical catalysis and computing, so the raw export was screened by hand. A record was kept only when its title, author keywords or abstract clearly dealt with incinerated bottom ash, incineration residues or their reuse as we get Total around 110. Screening left 69 relevant papers, and all of the quantitative results below are based on this set. For each paper the data were sorted in Microsoft Excel by document type, year, source title, publisher, author, affiliation, language, keywords and citation count. Keyword co-occurrence maps were produced in VOSviewer. Citation counts were taken on a single date and may differ a little if the search is repeated later.

Procedure of Analysis

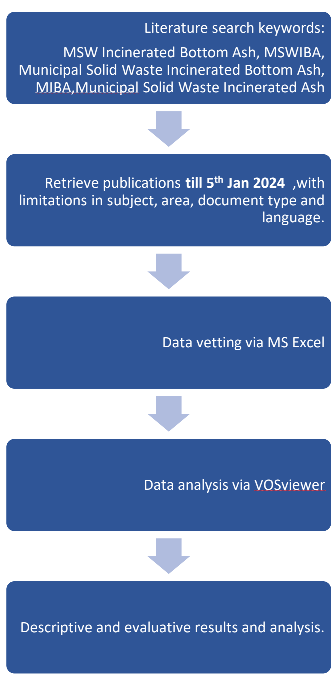

Fig 1 Methodology flowchart.

Scope note. The query uses exact phrases, so it returns a focused, high-precision slice of the field rather than the whole of it. Anyone wanting a larger set should widen the topic search to cover the common spelling variants.

3. Results

3.1. Countries Involved

The research is concentrated in a few countries. Table 1 shows China well in front, with 36 papers (52.2 percent of the set) and the most citations, which reflects both its large research base and the size of its WtE programme. Sweden and other European contributors, along with India and Taiwan, make up the rest of the leading group, and a few smaller contributors record high average citations. Across the set, authors from 25 countries took part, so the effort is global but spread unevenly. Figure 2 shows the VOSviewer Country-wise trend Globally

Country/Region	TP	TC	TC/TP	%
China	36	515	14.3	52.2%
Sweden	9	69	7.7	13%
Portugal	8	120	15	11.6%
India	4	18	4.5	5.8%
Taiwan	4	122	30.5	5.8%
United Kingdom	3	140	46.7	4.3%
Poland	3	18	6	4.3%
Brazil	2	55	27.5	2.9%
USA	2	1	0.5	2.9%
France	2	92	46	2.9%

Table 1. Ten most productive countries/regions in MSWIBA research.

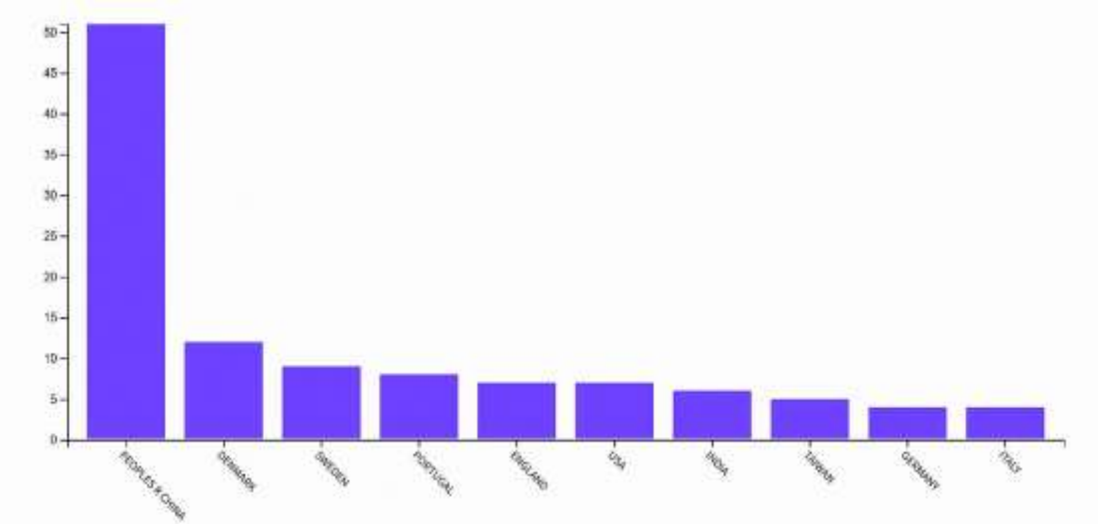

Fig 2 Bar Graph by WOS Country-wise trend Globally

3.2. Subject Category, Journals and Publishers

MSWIBA research sits across several disciplines. Table 2 shows that most of it falls under Environmental Sciences, Civil Engineering, Construction and Building Technology and Materials Science, with a fair share in Environmental Engineering. This spread fits the nature of the material, which is at once an environmental residue and a possible construction resource. Because a paper can be indexed under more than one category, the percentages add up to more than 100.

Subject Category	TP	%
Environmental Sciences	25	36.2%
Engineering, Civil	24	34.8%
Construction & Building Technology	24	34.8%
Materials Science, Multidisciplinary	24	34.8%
Engineering, Environmental	11	15.9%
Physics, Applied	6	8.7%
Green & Sustainable Science & Technology	4	5.8%

Subject Category	TP	%
Chemistry, Physical	3	4.3%
Metallurgy & Metallurgical Engineering	3	4.3%
Physics, Condensed Matter	3	4.3%

Table 2. Top subject categories by total publications (TP).

Table 3 shows that publication is concentrated in a few well-regarded journals. Construction and Building Materials is the most active by some distance, ahead of Waste Management and Science of the Total Environment. The latter two carry fewer papers but high average citations, which usually points to a small number of frequently cited, foundational studies.

Journal	TP	TC	TC/TP
Construction And Building Materials	16	282	17.6
Waste Management	5	160	32
Science Of The Total Environment	5	114	22.8
Journal Of Cleaner Production	4	39	9.8
Environmental Science And Pollution Research	4	23	5.8
Materials	3	21	7
Applied Sciences-Basel	3	10	3.3
Cement & Concrete Composites	2	128	64
Chemosphere	2	100	50
Journal Of Building Engineering	2	13	6.5
Buildings	2	9	4.5
Geomatics Natural Hazards & Risk	2	9	4.5
Journal Of Hazardous Materials	1	36	36
Apmis	1	30	30
Frontiers Of Environmental Science & Engineer…	1	28	28

Table 3. Most productive journals publishing MSWIBA research.

At the publisher level (Table 4), Elsevier imprints dominate, with MDPI next and Springer and Taylor & Francis also present. This matches the journal-level pattern.

Publisher	TP	%	TC	TC/TP
Elsevier Sci Ltd	22	31.9%	449	20.4
MDPI	12	17.4%	53	4.4
Elsevier	7	10.1%	82	11.7
Pergamon-Elsevier Science Ltd	7	10.1%	260	37.1
Springer Heidelberg	4	5.8%	23	5.8
Elsevier Science Bv	3	4.3%	89	29.7
Taylor & Francis Ltd	3	4.3%	9	3
Geomate Int Soc	1	1.4%	2	2
Higher Education Press	1	1.4%	28	28
Ice Publishing	1	1.4%	7	7
Natl Inst Science Communication-Nis…	1	1.4%	3	3
Quintessence Publishing Co Inc	1	1.4%	1	1

Table 4. Most active publishers in the MSWIBA field.

3.3. Authors and Language

Table 5 lists the most productive authors in the set, ranked by the number of papers they contributed and by the citations those papers received. The leading names belong to a few closely working groups, which fits the laboratory-heavy, team-based nature of the work. The citation figures here are summed over each author's papers within this set; a full author-level h-index would need a separate WoS query.

Author	TP	% of corpus	Citations (within corpus)
Zhang, WZ	10	14.49%	62
Liu, J	10	14.49%	62
Xing, F	10	14.49%	62
Li, ZL	9	13.04%	62
Jin, HS	8	11.59%	61
Poon, CS	7	10.14%	223
Silva, RV	7	10.14%	108
Tang, LP	7	10.14%	61
Xuan, DX	6	8.7%	173
de Brito, J	5	7.25%	101
Fan, X	5	7.25%	25
Phoungthong, K	4	5.8%	93
Zhang, H	4	5.8%	93
Shao, LM	4	5.8%	93
He, PJ	4	5.8%	93

Table 5. Most productive authors of MSWIBA-related research.

English is by far the main language of publication. Of the 69 screened papers, 69 are in English, so the field's international exchange runs almost entirely in English.

3.4. Author Keywords

Author keywords were counted overall and across three sub-periods to see how the vocabulary, and so the focus, changed over time. Table 6 shows that the leading terms describe the material itself and its main concerns, such as heavy metals, leaching and microstructure. The split by period brings out a shift: early work centred on characterisation and heavy-metal leaching, while recent papers more often use reuse-related terms like geopolymer, self-compacting concrete and carbonation. Figure 3 shows VOS Network Map of Keywords Intensity upon WOS screened dataset.

Keyword	Overall	2004-2010	2011-2016	2017-2023
municipal solid waste incineration bott…	13	1	1	11
heavy metals	7	0	0	7
bottom ash	7	0	2	5
mswiba	6	0	0	6
microstructure	5	0	0	5
municipal solid waste	5	0	0	5
fly ash	4	0	0	4
municipal waste incineration bottom ash	4	0	0	4
geopolymer	3	0	0	3
self-compacting concrete	3	0	0	3
incineration bottom ash	3	0	0	3
municipal solid waste incinerator botto…	3	0	0	3

Table 6. Top author keywords with temporal differentiation across three sub-periods.

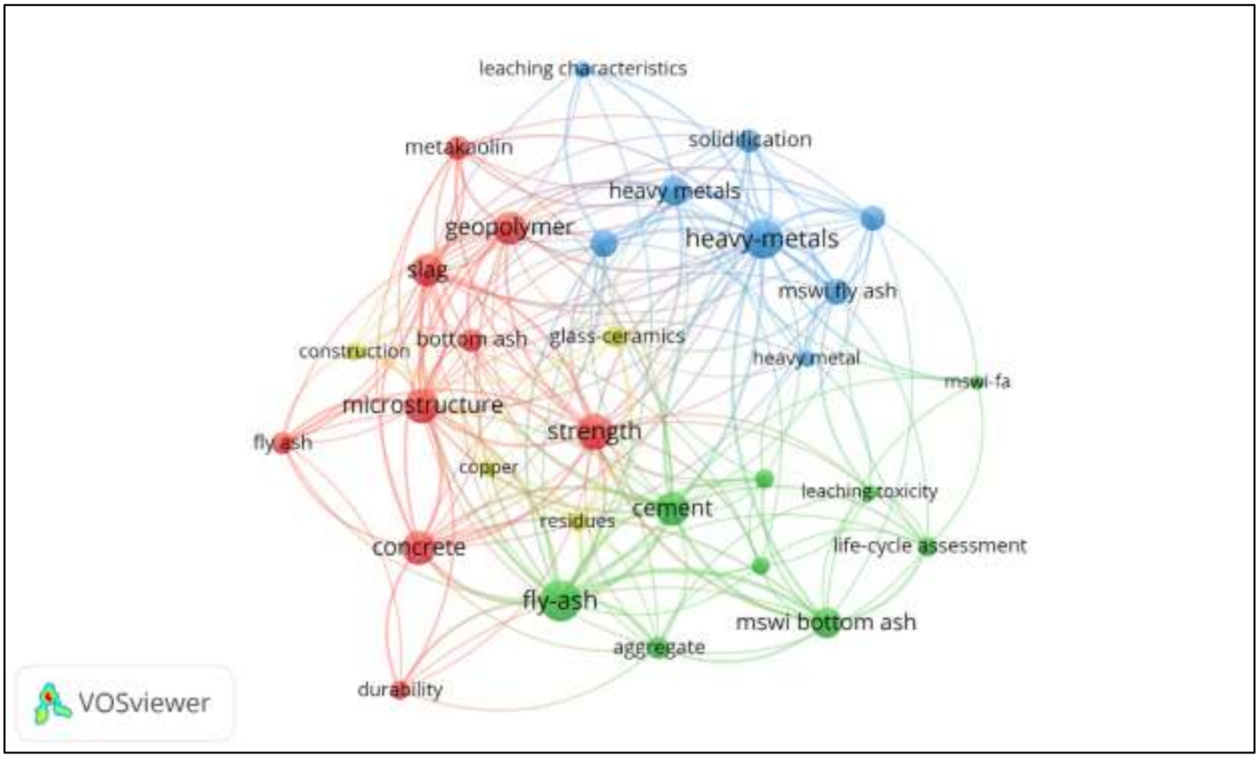

Fig 3 VOS Network Map of Keywords Intensity upon WOS screened dataset

3.5. Ten Most Cited Articles

Table 7 lists the ten most cited papers. The most cited, "Use of washed municipal solid waste incinerator bottom ash in pervious concrete." (2013), has 82 citations. The leading papers fall into two groups that have shaped the field: the characterisation and leaching behaviour of bottom ash, and its use as a partial substitute in concrete, cement and alkali-activated or geopolymer systems.

Article	TC	Year	Source
Use of washed municipal solid waste incinerator bottom ash in pervious concrete.	82	2013	Cement & Concrete Composites
Use of municipal solid waste incineration bottom ashes in alkali activated materials, ceramics and granular applications: A review	78	2017	Waste Management
Leachates of municipal solid waste incineration bottom ash from Macao: Heavy metal concentrations and genotoxicity	73	2007	Chemosphere
Municipal incinerated bottom ash characteristics and potential for use as aggregate in concrete	55	2016	Construction And Building Materials
Production of lightweight aggregate ceramsite from red mud and municipal solid waste incineration bottom ash: Mechanism and optimization	50	2021	Construction And Building Materials
Evaluation of the genotoxic, mutagenic and oxidant stress potentials of municipal solid waste incinerator bottom ash leachates	50	2004	Science Of The Total Environment
Municipal incineration bottom ash treatment using hydrothermal solidification	49	2007	Waste Management
Limitations and quality upgrading techniques for utilization of MSW incineration bottom ash in engineering applications - A review	47	2018	Construction And Building Materials
MSWIBA-based cellular alkali-activated concrete incorporating waste glass powder	46	2019	Cement & Concrete Composites

Article	TC	Year	Source
Biomonitoring of the genotoxic potential of aqueous extracts of soils and bottom ash resulting from municipal solid waste incineration, using the comet and micronucleus tests on amphibian (Xenopus laevis) larvae and bacterial assays (Mutatox and Ames tests)	42	2006	Science of the Total Environment

Table 7. Ten most cited articles in MSWIBA research (TC = total citations; Y = publication year).

3.6. Annual Output and Citation Features

This is a young field that has grown quickly. Table 8 shows that output through the 2000s was small and irregular, picked up in the mid-2010s, and then jumped after 2020, reaching 17 papers in 2022. The lower average citations for the most recent years are mainly a matter of time, since newer papers have had less chance to be cited, not a sign of falling interest. In total the 69 papers have gathered 1065 citations, about 15.4 per paper.

Year	Publications (P)	Total Citations (TC)	TC/P
2004	1	50	50
2006	1	42	42
2007	2	122	61
2008	2	41	20.5
2013	1	82	82
2015	1	27	27
2016	4	120	30
2017	2	85	42.5
2018	4	128	32
2019	2	49	24.5
2020	6	50	8.3
2021	12	139	11.6
2022	17	110	6.5
2023	14	20	1.4

Table 8. Year-wise publications and citation features.

3.7. Sustainability in Focus

One clear feature of recent MSWIBA research is how openly it ties into sustainability and the circular economy. Table 9 lists representative papers that frame bottom-ash reuse in terms of recycling, valorisation, green materials, carbon reduction or the circular economy. Their dates show this framing becoming more common through the late 2010s and into the 2020s, in step with the keyword shift noted in Section 3.4, and placing bottom-ash reuse within the wider waste-to-resource agenda.

Source Title	Publisher	Year	TC
Construction And Building Materials	Elsevier Sci Ltd	2016	55
Slovak Journal of Civil Engineering	Sciendo	2020	0
Innovative Infrastructure Solutions	Springer Int Publ.	2021	12
Construction And Building Materials	Elsevier Sci Ltd	2021	14
Construction And Building Materials	Elsevier Sci Ltd	2021	9
Case Studies in Construction Materi…	Elsevier	2022	5
Journal Of Building Engineering	Elsevier	2022	9
Materials	MDPI	2022	6
Buildings	MDPI	2022	8
Journal Of Cleaner Production	Elsevier Sci Ltd	2022	27

Source Title	Publisher	Year	TC
Journal Of Cleaner Production	Elsevier Sci Ltd	2022	6
Energies	MDPI	2022	4
Science Of the Total Environment	Elsevier	2022	5
Science Of the Total Environment	Elsevier	2022	12
Construction And Building Materials	Elsevier Sci Ltd	2022	12

Table 9. Representative sustainability- and circular-economy-oriented publications in the corpus.

3.8. Significance of the Analysis

A bibliometric study like this has both scientific and practical value. By counting citations and output it gives an objective sense of which papers, journals, authors and countries have shaped the field. By mapping co-authorship and keywords it shows the collaboration networks and the emerging themes, which can help direct future effort and funding. For practitioners and policymakers, the dataset assembled here points to where the evidence for safe, standards-compliant reuse is strongest and where more work is still needed.

4. Discussion: Thematic Review of the MSWIBA Literature

Alongside the counts above, the wider MSWIBA literature can be grouped under four headings, composition and characterisation, treatment, engineering applications, and regulation, which together explain how bottom-ash reuse has moved from a disposal problem to a resource.

4.1. Composition, Characterisation and Treatment

Bottom ash is a mixed, coarse and porous material. Its chemistry is dominated by SiO_2, CaO, Al_2O_3 and Fe_2O_3, which together usually make up more than 60 percent of its mass and put its overall composition close to that of Class C coal fly ash (Chen et al., 2023; Bayuseno and Schmahl, 2010; Wei et al., 2011). Fresh ash is alkaline, with a pH near 12, and tends to leach heavy metals such as Pb, Zn and Cu; residual metallic aluminium can also react to give off hydrogen, which limits direct use. Weathering, or ageing, at the plant over one to three months lowers the pH towards neutral, forms stable secondary phases such as calcite, ettringite and metal hydroxides, and cuts leaching (Yao et al., 2012; Sabbas et al., 2003; Chen et al., 2023). In the laboratory, grinding and sieving, water and alkaline (NaOH) washing, acid washing and thermal treatment between 500 and 1500 degrees Celsius improve uniformity, remove soluble salts and metallic aluminium, and raise reactivity (Saikia et al., 2015; Tang et al., 2016; Xuan et al., 2018; Dou et al., 2017). Recovering metals from the ash, increasingly through closed-loop routes for Zn and Cu, has itself become an active topic (Syc et al., 2020; Perrin et al., 2023; Biganzoli et al., 2013; Saffarzadeh et al., 2016; Blasenbauer et al., 2023). Detailed studies of chloride speciation and mineral phases support this picture (Alam et al., 2019, 2020).

4.2. Engineering Applications

Most commonly, bottom ash has been used in road and pavement construction. Treated bottom ash can be used as unbound sub-base, base and embankment course materials, as well as subgrade materials (Lynn et al., 2017; Vegas et al., 2008; Le et al., 2018). Specifically for Indian ash, Gupta et al. (2021) reported that Indian ash offers good bearing and shear strength for pavement and embankment constructions, while Singh and Kumar (2020) showed that the ash's geotechnical behavior can be improved by cement and fiber. In cement and concrete, bottom ash can be used as a partial aggregate, a supplementary cementitious material (SCM), as well as a precursor for the production of alkali-activated and geopolymer binders (Bertolini et al., 2004; Lin and Lin, 2006; Pan et al., 2008; Gao et al., 2017; Tang et al., 2020; Maldonado-Alameda et al., 2020; Casanova et al., 2021; Zhang et al., 2021). The pozzolanic and alkali-activation of weathered ash has been compared with that of Class F coal fly ash. Thus, the weathered ash can also be used as fly ash in construction (Chen et al., 2023). Bottom ash has also been used in lightweight and cold-bonded aggregates, in cement clinker, as landfill cover, as land reclamation materials, and in other products such as glass-ceramics and adsorbents (Qiao et al., 2008; Kumar and Singh, 2021). Recent studies continue to improve on the classification and screening of bottom ash for these purposes (Chen et al., 2024).

4.3. Environmental Safety and Regulation

The main hurdle to large-scale reuse remains dealing with the possibility for heavy metals and salts to leach into soil and groundwater. Risks must be managed through prescribed treatments and testing before and after reuse (Verbinnen et al., 2017; Zhu et al., 2021). There is considerable variability from country to country in ash bottom treatment in Europe. Many treat bottom ash as non-hazardous and permit bound and unbound uses of ash in construction. These countries typically impose leaching limits and, in some cases, a mandated maturation period. For the most part, specific leaching and maturation limits vary from country to country (Blasenbauer et al., 2020; Kumar and Singh, 2021). This fragmented approach and the inconsistent composition of bottom ash lead to uneven adoption and use of ash. Several authors have suggested that a unified classification system and property database be created to facilitate ash bottom reuse (Chen et al., 2023).

5. Conclusions

This study applied bibliometric analysis to the MSWIBA literature in the Web of Science Core Collection, working from a screened set of 69 relevant papers published between 2004 and 2023, and added a short thematic review of the wider field. The main points are as follows.

1. MSWIBA research is young and growing fast. Output was small before the mid-2010s and rose sharply after 2020, and the 69 papers have together attracted 1065 citations (corpus h-index 19).
2. The journal article is the main document type, and the work clusters in Environmental Sciences, Civil Engineering, Construction and Building Technology and Materials Science, in line with the material being both a residue and a resource.
3. Publication is concentrated, led by Construction and Building Materials and by Elsevier imprints, and English is almost the only language used.
4. China leads on both output and citations, ahead of European contributors, India and Taiwan; the work is global but spread unevenly across 25 countries.
5. The keyword and most-cited-paper results show the focus moving from heavy-metal leaching and characterisation towards valorisation, geopolymerisation and supplementary cementitious use.
6. The thematic review confirms road construction, cement and concrete substitution and alkali-activated materials as the most developed applications, with weathering and thermal or chemical treatment as the main enablers and heavy-metal leaching and uneven regulation as the main barriers.
7. Sustainability and the waste-to-resource idea run through much of the recent work, linking bottom-ash reuse to SDG 11, 12 and 13 and to resource-efficient construction.

Like any bibliometric study, this one looks backward, leans on counts and citations, and is limited by a single database, a single search date and a narrow, exact-phrase query. A wider search, as set out in Section 2, would enlarge the set. Even so, by mapping the structure and direction of the field and drawing together its main themes, the study gives a starting point for further experimental and standards-based work on the safe and sustainable reuse of incinerated municipal solid waste bottom ash.

Declarations

Data Availability: The bibliographic data analysed in this study were retrieved from the Web of Science Core Collection database.

Conflicts of Interest: The authors declare no conflict of interest.

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