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Hospital waste incinerator ash: characteristics, treatment techniques, and applications (A review)

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ABSTRACT

The amount of medical waste generated has increased enormously since the COVID-19 outbreak. An incineration process is the main method that is usually used to treat this waste, causing an increase in both medical waste bottom ash (MWBA) and medical waste fly ash (MWFA). In this work, the physical and chemical characteristics of MWFA and MWBA were reviewed. This ash contains high levels of polychlorinated dibenzo-p-dioxin (PCDD), dibenzofurans (PCDFs), and heavy metals. Furthermore, medical waste ash appears to have high leachability in the toxicity characteristics leaching procedure (TCLP) test and the European standard test (EN 12457). Owing to its toxicity, medical ash can be treated using various methods prior to disposal based on the covered review. These techniques include chemical, supercritical fluid, cement-based, melting, microwave, and mechanochemical techniques. The shortcomings of some of these treatment methods have been identified, such as the emission of high levels of chlorine from the melting technique, limited applications of the flotation method on the industrial scale, long-term stability of leachate treated by cement-based methods that have not been confirmed yet, and high energy consumption in the supercritical technique. This review also covers possible applications of medical waste ash in cement production, agriculture, and road construction.

Key words: ash treatment, bottom ash, dioxin, fly ash, heavy metals, medical waste

HIGHLIGHTS

- Medical waste ash contains high concentrations of dioxins.
- Heavy metals in medical waste ash have a high leachability in the soil and groundwater.
- Further investigations to solve multiple problems in treatment techniques of medical waste ash are required.
- Medical waste ashes have been found to be beneficial in concrete production.

GRAPHICAL ABSTRACT

INTRODUCTION

Since December 2019, the COVID-19 pandemic has significantly increased the volume of medical waste generated worldwide. Each country has experienced a massive rise in medical waste produced by healthcare facilities. For instance, in Wuhan, China's COVID-19 epicenter, the amount of medical waste generated from hospitals and other healthcare centers increased from 40–50 to 247 tons/day on 1 March 2020 (Peng *et al.* 2020). In Bangladesh, the second most affected by COVID-19, the volume of medical waste has increased from 658 tons in March 2020 to 16,164.74 tons in April 2021. On a daily basis during the pandemic, the USA produced 8,055.3 tons/day, India 2,160.34 tons/day, and Brazil 2,774.35 tons/day (Chowdhury *et al.* 2022; Etim *et al.* 2022). Globally, the volume of medical waste has increased for a second time during vaccination. For example, it was estimated that 135.9 tons of waste were produced during the first vaccination dose in Bangladesh (Chowdhury *et al.* 2022).

The term medical waste covers all waste produced in healthcare or diagnostic activities (Twinch 2011). For example, the Ministry of Health of Jordan defines medical waste as solid, liquid, and gaseous waste generated in healthcare facilities, dental practices, medical research centers, pharmaceutical industries, blood banks, and veterinary clinics (Abu Qdais *et al.* 2007). Medical waste can be classified into different categories: (i) pathological waste, which includes organs, body parts, and human tissues, (ii) sharps including needles, syringes, and blades, (iii) chemicals, such as solvents used for laboratory preparation and heavy metals from medical devices, and (iv) infectious waste, such as body fluids. Approximately 70–90% of medical waste is harmless and comparable to household waste. The remaining 10–25% is classified as hazardous and poses environmental and health risks (Padmanabhan & Barik 2018).

The US Environmental Protection Agency (EPA) has warned that medical waste should be treated using special methods, and any improper treatment of waste can threaten human health and cause serious environmental problems (Ghanimeh *et al.* 2019). Incineration is the most common treatment method for medical waste and is used worldwide. However, not all medical waste can be treated using incinerators, such as organs, body parts, and human tissues, which require different types of treatment (Vasistha *et al.* 2018). Incineration is an oxidation process at high temperatures, at which the inorganic and organic contents are reduced. The incineration process is usually used when the waste cannot be reused, recycled, or disposed of in landfills (Hasselriis & Constantine 1992).

Incinerators are classified into three main categories: (i) controlled air incinerators are the most widely used in medical facilities, (ii) excess air incinerators, and (iii) rotary kiln incinerators. A controlled air incinerator consists of two main stages: the first one is the primary combustion chamber, in which the combustion gas temperatures are between 760 and

980 °C. At this stage, the waste is fed into a chamber where limited amounts of air are used, usually less than the stoichiometric amount of air required. Excess air was typically used in the second stage. The temperature of the second stage (chamber) was higher than that in the first stage, with a maximum temperature of 1,095 °C (Allen *et al.* 1986). The main advantage of incineration treatment is that it reduces the volume of waste; 80% of medical waste volume can be reduced using incinerators, and incineration can destroy pathogens and hazardous organics. However, incineration has some drawbacks: it releases a wide variety of unwanted pollutants from burning medical waste, which may pose a significant risk to the environment and human health (Lee & Huffman 1996).

Medical waste incineration products can be divided into two main parts. The first part is the waste that is released to the external environment, such as fly ash (MWFA), carbon dioxide, sulfur oxides, and chlorides. The second part is the ash left in the incinerator, called bottom ash (MWBA). The ash remaining in the incineration chamber constitutes 75–90% of the total ash (Jaber *et al.* 2021). The nature of both the fly and bottom ash was examined and analyzed through multiple chemical analyses. The main analyses determined the metal content in the ash, particle size distribution, mineralogy, and leaching of metals.

The objectives of this review are to represent the chemical and physical characteristics of fly and bottom medical waste ashes, compare the treatment techniques used to reduce the toxicity of medical waste ashes, show the possible applications of hospital waste ashes specifically in concrete production, road construction, and agriculture. In more detail, the review highlights all studies conducted to increase the compressive strength of concrete made using medical waste ash (MWA) as a partial replacement. The review will also cover the missing research activities that should be carried out in the future.

MEDICAL WASTE BOTTOM ASH

The bottom ash has a black-gray color with a density range of 0.73–1.94 kg/m^3 (Tsakalou *et al.* 2018). Multiple studies have indicated that the pH of bottom medical waste ash (BMWA) is remarkably alkaline ($pH = 8–12$). Sometimes, it exceeds the legal limit and must be placed in a special concrete landfill (Ni *et al.* 2013; Miao *et al.* 2022).

Particle size distribution of bottom ash

Gidarakos *et al.* (2009) found that most bottom ash particles were incombustible matter with a particle size of up to 9.5 mm and accounted for 52.55% (W/W) of total bottom ash particles, while the remaining particles have sizes less than 4.75 mm. The reasons for the presence of incombustible matter in their study were insufficient incineration time, insufficient air quality, and low temperature inside the combustion chambers. On the other hand, finer particles were observed in a case study in Wuhan, China, regarding the characteristics of bottom ash of COVID-19, showing that more than 90% of the total bottom ash particles were smaller than 225 μm (Miao *et al.* 2022). A study from Greece also found that most bottom ash particles were fine particles with a size fraction of up to 250 μm (Tsakalou *et al.* 2018).

A study from India collected samples from 13 common biomedical waste treatment facilities across India, indicating that approximately 62% of the bottom ash mass had a size of less than 1,000 μm (Kumar *et al.* 2021). Comparable results were found in another study, where more than half of the total particles in the bottom ash had a particle size distribution ranging from 250 to 1,000 μm (Bakkali *et al.* 2013).

Chemical characteristics of bottom ash

Oxides content

Many studies have been conducted to determine the chemical composition of bottom ash generated from the incineration of medical waste. The chemical composition of ash depends on the type of original medical waste, the incineration process type, and its temperature. Tsakalou *et al.* (2018) used X-ray fluorescence to identify the chemical composition of BMWA and found that silicon oxide (SiO_2) is the major chemical compound of the bottom ash (57.5 wt.%), and the remaining are CaO (19.34 wt.%), Al_2O_3 (7.32 wt.%), and traces of Fe_2O_3, MgO, K_2O, and Na_2O. Other studies from Greece and Turkey also agreed with the previous one and found that SiO_2 and CaO are the major oxides in the MWBA, with a total weight fraction of both oxides up to 67.51 wt.% (Akyıldız *et al.* 2017). Gidarakos *et al.* (2009) showed that their bottom ash samples contained high levels of calcium oxides. Additionally, the authors investigated the relationship between the particle size of MWBA and the oxide content. In the larger particles (>1 mm), the silicon oxide content increased, whereas calcium oxide was observed in the fine particles (less than 0.25 mm). Also, Debrah & Dinis (2023) studied the chemical characteristics of bottom from biomedical waste incineration in Ghana, and they concluded that the chemical composition of the analyzed bottom ash samples was $CaCO_3$ (49.90%), CaO (27.96%), $MgCO_3$ (6.02%), MgO (2.87%), SO_3 (2.34%), and SO_4 (2.80%). However, the high concentration of $CaCO_3$ in this study, with a mean of 49%, may be due to the presence of papers in incinerating BMWA (Chang *et al.* 2017; Debrah & Dinis 2023). It could also be due to the presence of the marbles in constructing the incinerator (Hashimoto *et al.* 2017; Krajewska 2018; de Oliveira *et al.* 2021) and possibly through the use of $CaCO_3$ dietary supplements in the form of medication by patients (Salomão *et al.* 2017; Zhai *et al.* 2018).

Although many studies have shown that SiO_2 is the main oxide in bottom ash samples and has the highest concentration among other oxides, a higher CaO concentration has been reported in India, with mass fractions of approximately 39 and 14% for SiO_2 (Kumar *et al.* 2021). A fluctuation in the percentage of oxides was obvious in the Bakkali *et al.* (2013) study, where samples from one incinerator consisted of phosphorous pentoxide (P_2O_5), while samples from the other consisted mainly of SiO_2 and CaO, owing to the difference in the nature of the medical waste fed to the incinerators, Table 1 presents the oxide concentrations in MWBA found in previous studies.

The composition of MWA, which primarily consists of CaO rather than calcium carbonate ($CaCO_3$), makes it a favorable choice for cement production. This was attributed to the reduced carbon dioxide emissions associated with employing CaO in cement manufacturing, in contrast to the substantial emissions linked to $CaCO_3$.

The silicon–calcium (Si/Ca) ratio of BMWA has been measured in many studies as an indicator of the degree of mixing of municipal waste with medical and biomedical waste. For example, a study from China measured the Si/Ca ratio and found that its value is less than one, while typical medical solid waste bottom ash has a Si/Ca ratio greater than three because of the difference in the composition of municipal waste and medical waste (Zhao *et al.* 2010).

Heavy metals

Heavy metals in medical waste are usually not destroyed by the incineration process but they are concentrated in the bottom ash. Heavy metals in bottom ash come from various sources, such as zinc (Zn) from batteries, nickel (Ni) from stainless steel needles, and the presence of chromium (Cr), which may indicate the existence of plastic in medical waste. The concentrations of heavy metals vary enormously from study to study, according to Jung *et al.* (2004) and Javied *et al.* (2008). This variation is due to two reasons: first, incineration operating parameters (furnace temperature, furnace type, and capacity), second, the nature of medical waste fed to the incinerator, and third, the experimental parameters for heavy metals content analysis (sample perpetration and analytical method). In another work, Amfo-Otu *et al.* (2015) measured the concentration of heavy metals in BMWA. The samples in this study were collected from four hospitals in Ghana and analyzed using atomic absorption spectroscopy (AAS). The analysis showed that lead (Pb) and chromium (Cr) were present in large amounts in the samples, with average concentrations of 108.59 and 33.1 mg/kg, respectively. Mercury (Hg) had a minor concentration in the bottom ash samples. High quantities of Pb, Cr, Zn, and Ni were also observed in a study by Morocco, where the samples were collected from two different incinerators (Bakkali *et al.* 2013). On the other hand, iron (Fe) had the highest concentration in studies by Honest *et al.* (2020) and Selman *et al.* (2021), with a concentration range of 758–3,148 mg/kg, and nickel was the lowest; bottom ash samples were collected from six healthcare centers and analyzed using inductively coupled plasma optical emission spectroscopy (ICP-OES). The same results, where iron was the largest concentration, were detected in a recent study from Iraq; the heavy metal content was determined using AAS; iron concentration in the study ranged between 25.3 and 76.6 μg/g. The presence of iron in the bottom ash is because iron is the major element of medical needles (Selman *et al.* 2021).

Table 1 | Chemical analysis of MWBA

SiO_2 (%)	CaO (%)	Al_2O_3 (%)	MgO	Fe_2O_3	Na_2O	Reference
57.52	19.34	7.32	1.83	1.18	6.5	Tsakalou *et al.* (2018)
37.58–47	25–32.5	10.82–13.7	–	–	4.39–12.24	Gidarakos *et al.* (2009)
17–23[a]	14–20	8–15	3	1–3	8–16	Bakkali *et al.* (2013)
14	39	6	4	3	13	Kumar *et al.* (2021)
26.1	30.5	10	6	6	<8.8	Zhao *et al.* (2010)

[a] Medical wastes from two different hospitals.

Some studies have investigated the relationship between particle size and the heavy metal content of MWA. Fine particles were found to be enriched with lead, whereas medium-to-large particles consisted of iron (Racho & Jindal 2004; Allawzi *et al.* 2018). Racho & Jindal (2004) explained these results based on the melting point, where lead has a lower melting point (328 °C), so it would convert totally into small particles of ash. Iron, on the other hand, has a high melting point that may reach 1,538 °C; therefore, it cannot melt completely but could break at the incinerator's temperature.

Mineralogy of bottom ash

Using X-ray diffraction (XRD), Akyıldız *et al.* (2017) found that the main minerals in bottom ash were halite (NaCl), mayenite ($Ca_{12}Al_{14}O_{33}$), rondorfite ($Ca_8Mg(SiO_4)_4Cl_2$), titanium chloride ($TiCl_3$), and calcium aluminosilicate ($CaAl_2Si_2O_8$), which is consistent with another study. For example, in the study by Anastasiadou *et al.* (2012), halite was the major mineral; however, unlike other studies, hematite was strongly present in the bottom ash.

Metals leachability from bottom ash

A study of metal leaching from bottom ash is necessary to evaluate the degree of danger of ash. Multiple procedures should be performed to minimize the leaching of hazardous components into the soil. Moreover, proper management procedures should be applied before ash is disposed of in landfills. Leaching tests are used to evaluate potential contaminant release from hospital incinerator ash. Several leaching tests are used to assess the characterization of MWA, such as the toxicity characteristics leaching procedure (TCLP) test, the Japanese standard leaching test (JLT-13), and the European standard test (EN 12457). The TCLP test was used to investigate the leachability of heavy metals from the BMWA. According to the EPA, the TCLP is designed to determine the mobility of organic and inorganic compounds present in liquid, solid, and multiphase waste (United States Environmental Protection Agency (USEPA) 1992). In the TCLP test, the solid waste sample was mixed with an acetic acid solution at a liquid–solid ratio of 20 ml/1 g and shaken with a rotary tuber for 18 h (Ghosh *et al.* 2004).

In Tsakalou *et al.*'s (2018) study, TCLP's results indicated that lead had the highest affinity and could not meet the quality standards discharged to the landfill, while other metals in the study showed a relatively stabilized behavior. However, in Zhao *et al.*'s (2009) study, the TCLP results showed that BMWA could not cause harmful effects, and all heavy metals in the leachates did not exceed the United States Environmental Protection Agency (USEPA) regulatory limits, as represented in Table 2.

Many tests can be performed to analyze the leachability of heavy metals from bottom ash. EN 12457 and Leaching Toxicity-Sulfuric Acid and Nitric Acid Method (HJ/T 299-2007) tests were used alongside TCLP to study the affinity of heavy metals from bottom ash produced during the COVID-19 pandemic. The TCLP results showed that only three heavy metals were detected in the leachates (Ba, Pb, and Cr), whereas the other tests indicated that leachates were enriched with Na, Ca, and K (Miao *et al.* 2022). According to Miao *et al.* (2022), these results were predictable owing to the presence of CaO, Na_2O, and K_2O in BMWA.

Table 2 | Leaching tests and their heavy metal concentrations in leachate from MWBA

	Toxicity characteristic leaching procedure (TCLP)				**European standard test (EN 12457)**	
method	**Concentration (mg/L)**			**Limit (mg/L)**	**Concentration (mg/L)**	**Limit (mg/L)**
Cr	4.25	0.01–3.9	0.128	5	3	1
Cd	0.04	0.01–0.65	0.0006	1	<1	0.1
Pb	7.25	0.02–1.8	0.005	5	1	1
Zn	27.3	0.99–8.73	0.1911	100	36	5
Cu	53.70	0.15–4.8	1.55	100	39	5
As	2.2	–	–	5	–	0.2
Ba	25.2	0.46–22	2.4399	100	69	10
Reference	Tsakalou *et al.* (2018)	Racho & Jindal (2004)	Tzanakos *et al.* (2014)		Valavanidis *et al.* (2008)	

Other studies have investigated the effects of certain parameters on the leaching of heavy metals from BMWA (Xie & Zhu 2013; Allawzi *et al.* 2018). For example, the effect of pH has been studied by conducting experiments at various pH levels. The analysis showed that in the pH range between 3 and 11, Hg, As, and Se appeared significantly in leachates, while other metals did not show any exact pattern with pH (Xie & Zhu 2013). Other parameters and their effects on the leachability of heavy metals have also been studied by Allawzi *et al.* (2018). The parameters in this study were the contact time, S/L ratio, particle size, initial pH, and temperature.

There was a direct correlation between the contact time and the concentrations of some heavy metals (Cr, Sr, Cu, and Ni) in the leachate. However, the Zn and Al contents in the leachate dropped sharply with time owing to the formation of solid participants. The Fe, Mo, Rb, Pb, Se, and Zn concentrations in the leachates were negatively related to particle size. Moreover, it was found that the relationship between the initial pH, temperature, and heavy metal levels in leachates did not follow a specific pattern.

MEDICAL WASTE FLY ASH

Fly ash is an incineration residue that accounts for approximately 3–5 wt.% of the original waste's total mass and is collected by the waste incineration system's bag filter (Liu *et al.* 2018).

Particle size distribution of fly ash

The fly ash particles from the medical waste incinerators were very fine. The investigation of particle size distribution in previous studies mainly used sieving analysis, and some of them used laser diffraction spectroscopy for the <100 m fraction. Vavva *et al.* (2017) found that 96% of the total weight of fly ash collected from incinerators in Greece had particle sizes below 100 μm, with a median particle size of 20 μm. This result was comparable to those of other studies. Cobo *et al.* (2009) demonstrated that the size of 75 wt.% of fly ash resulting from the combustion of the medical and industrial waste mixture was less than 100 μm. Some studies have shown that most fly ash particles are below 56 μm (Tsakalou *et al.* 2018). However, another study has shown the presence of fly ash sizes in a larger range. In China, fly ash samples from two incinerators were analyzed, and it was found that the particles mainly ranged from 15 to 900 μm (Tan & Xiao 2012).

Chemical characteristics of fly ash

Elemental composition

The chemical content of fly ash depends on the type and amount of medical waste fed to the incinerator and the operating parameters of the incinerator. The heavy metal content and elemental composition of fly MWA can be determined using ICP-OES and AAS. Zhao *et al.* (2009) analyzed the content in the hospital waste incinerator ash. The analysis indicated the presence of high content of main elements, including Na, which has the highest concentration, while Ca, K, and Mg had concentrations ranging from 3 to 221 g/kg.

This result is in good agreement with those of other studies. For instance, the ICP-MS results of Jin *et al.* (2010) showed that Ca, Mg, and Na were the major elements in fly ash. However, unlike Zhao *et al.* (2009) in this study, Cl was strongly present, with concentrations of up to 16.48%; similarly, high chloride content reached up to 30% in other studies (Liu *et al.* 2013; Akyıldız *et al.* 2017). Table 3 summarizes the heavy metal concentrations in medical waste fly and bottom ash found in the literature.

Dioxins in MWA

Polychlorinated dibenzo-p-dioxin (PCDD) and dibenzofurans (PCDFs) (Figure 1) or PCDD/Fs, which are usually referred to as dioxins, are carcinogenic and have adverse effects on infant development and human reproduction. It is generally produced through three main mechanisms: (1) precursor transformation, which occurs due to the polycondensation of precursors, such as polychlorophenols, polychlorobenzene, polycyclic aromatic hydrocarbons (PAHs), and polychlorinated diphenyl ethers (PBEs) in the temperature range of 300–600 °C (Everaert & Baeyens 2002). (2) *De novo* synthesis, in this mechanism, PCDD/Fs are formed under moderate temperatures between 200 and 400 °C in the presence of oxygen, carbon, and chlorine and activated by copper (Stieglitz *et al.* 1989; Wang *et al.* 2012). (3) Incomplete combustion of chlorinated plastic (Thornton *et al.* 1996). Owing to its harmful impacts, various methods have been developed to decompose PCDD/Fs, including the mechanochemical method, thermal treatment using different heating temperatures, and the destruction of dioxins using Nano-TiO_2 based V_2O_5/CeO_2 catalysts (Yan *et al.* 2007; Yu *et al.* 2016; Chen *et al.* 2020).

Table 3 | Heavy metal concentrations in MWFA and MWBA in mg/kg

Type of MWA	Ni	Pb	Cd	Cr	Cu	Zn	Fe	Reference
MWFA	21.33–100.29	1,173.89–3,619.91	31.93–157.27	32.14–153	156.86–598.31	4,613.55–11,174.35	–	Ni *et al.* (2013)
MWFA	20–57.3	900–5,400	28.9–635	3.5–264	420–2,900	28,800–121,000	9,200–29,500	Zhao *et al.* (2009)
MWFA	240.85	7,389.98	93.98	228.99	473.89	34,464.48	14,150.32	Cobo *et al.* (2009)
MWFA	755.55	1,175.95	32.2	–	1,255.1	749.22	–	Tan & Xiao (2012)
MWFA	22.4	135.5	3.3	–	138.2	1,103	–	Tsakalou *et al.* (2018)
MWFA	154	3,160	126	19	1,880	52,310	14,160	Xie & Zhu (2013)
MWFA	198	1	<1	178	2,397	8,234	7,500	Valavanidis *et al.* (2008)
MWBA	124	18	3.2	–	1,287	52.7	–	Tsakalou *et al.* (2018)
MWBA	62	2,050	5.9	84	1,100	5,650	2,010	Valavanidis *et al.* (2008)

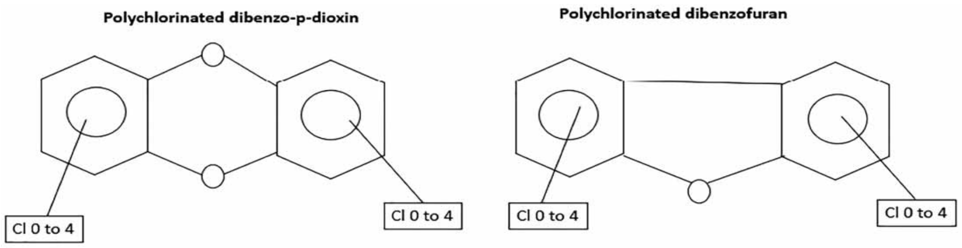

Figure 1 | Chemical structure of dioxins.

Dioxins in MWA are a major concern. According to the USEPA, medical waste is the third prime source of dioxin emissions in the US. Supplementary Table 4 indicates that MWFA contains a larger amount of total dioxins than MWBA does. The PCDD/F concentrations in fly ash range between parts per trillion and parts per billion, while its level in bottom ash is usually about parts per trillion (Du *et al.* 2013).

Metals leachability of fly ash

Tan & Xiao (2012) used the parameters that might affect the leaching of fly ash. The parameters under study were the liquid–solid ratio, initial pH, particle size, and leaching time. It was found that Cr, Hg, Pb, and Cd concentrations were directly correlated with contact time. Moreover, the concentrations of the same heavy metals, such as Cu and Mn, increased significantly with the solid–liquid ratio.

Sequential extraction is another test used to assess the potential effect of medical waste ashes. In sequential extraction, the metals are fractionated into five successive fractions (exchangeable fraction, bound to carbonate, bound to iron a manganese oxide, bound to organic matter, and residual). At each fraction, the conditions were designed to simulate the environmental conditions (Tessier *et al.* 1979). Each fraction of them differs in the reagent used for the extraction process, contact time, and pH values.

Sukandar *et al.* (2006) used sequential extraction and the TCLP test to evaluate the leaching amount of metals at various particle sizes and indicated that some metals tend to bind to some extraction fraction stage at specific particle sizes. For instance, Cr, Pb, and Zn are bound to Fe–Mn oxides at 150–106 μm. In contrast, Ba prefers extraction at an exchangeable fraction. However, the TCLP method did not result in a difference in the leachability of Cd, Cr, Cu, Ni, Hg, and Zn at different particle sizes.

Some studies compared the leachability of fly with bottom ash of medical waste, such as Tsakalou *et al.* (2018) article, their TCLP's result showed that Ba, Cr, and Zn in fly ash had higher mobility than bottom ash and exceeded EPA TCLP regulatory limits. Zhao *et al.* (2009) also indicated that fly ash might cause more environmental concerns than bottom ash, and it needs proper treatment before disposal.

In addition to the TCLP test and sequential extraction method, a physiologically based extraction test (PBET) was conducted to examine the risk of heavy metals in medical waste ashes. PBET was developed to predict the bioavailability of heavy metals in animal models. The PBET procedure included the simulation of gastric digestion using a separatory funnel filled with stomach solution placed in a temperature-controlled water bath at 37 °C. Argon gas was purged into the separatory funnel, and the pH was controlled and adjusted to the target value (Ruby *et al.* 1996).

The PBET method was conducted by Xie & Zhu (2013) using the TCLP test to assess the environmental risk of heavy metals in fly MWA. Samples were collected from medical waste incinerators in China. Surprisingly, the results of both methods were contradictory. The TCLP demonstrated that Cd, Pb, and Zn had high leaching potentials and exceeded the regulatory limit. However, PBET indicated that the heavy metals in fly ash had a low health risk level.

The high mobility of Pb and Cd in the leaching test was also observed by Kougemitrou *et al.* (2011), where ashes were collected from medical waste incinerators in Athena, and it was found that fly ash required additional treatment before disposal. However, some studies did not show compatible results; for example, Vavva *et al.* (2020) demonstrated that Pb alone had a high leaching potential to the soil and might cause environmental risk, while other metals did not exceed the limit. Another study by Vavva *et al.* (2017) demonstrated that even in fly municipal waste ash, Pb exceeded the legal limit values for waste landfilling. Supplementary Table 5 presents the results of the leaching tests conducted on the MWFA.

STABILIZATION TECHNIQUES

Medical waste ashes treatment can be classified into three main categories: (1) Solidification/stabilization (S/S), which includes chemical stabilization and cement-based techniques. (2) Thermal treatments include melting, sintering, and microwave treatments. (3) Separation techniques, including washing.

Chemical stabilization

The chemical stabilization technique reduces the environmental risk of toxic materials by introducing chemical agents that convert poisonous substances into forms with less toxicity and solubility through chemical reactions. Various chemicals were used to stabilize the ashes produced from municipal solid waste incineration, such as sodium sulfide, thiourea, ethylenediaminetetraacetic acid disodium salt (EDTA), sodium hydroxide, phosphate, and different silica-containing materials. Chemical stabilization has proved to be a successful method for converting soluble and toxic metals from ashes to insoluble and nontoxic forms (Youcai *et al.* 2002; Geysen *et al.* 2004; Wang *et al.* 2018).

Phosphate-based stabilization is one of the most promising and thoroughly researched chemical stabilization approaches (Zacco *et al.* 2014). The basic principle of phosphate-based stabilization is the attachment and immobilization of metals in the phosphate mineral matrix (Vavva *et al.* 2017). Acidic phosphoric acid and alkaline phosphoric acid have been used as chelating agents to stabilize heavy metals in fly ash samples collected from incinerators in Japan. The effectiveness of the three chemical reagents was tested using a modified leaching test conducted in Japan (JLT-13). The results indicated that the three chemicals successfully reduced the concentration of fluid, reducing the concentrations of Pb in leachate to below the regulatory limit, and the toxicity of leachate also decreased significantly after using chemical reagents (Sukandar *et al.* 2009).

The phosphate stabilization method was used in conjunction with the water-washing technique, washing with water is a method used to remove dissolved salts. This modified method involves the utilization of 7, 10, and 12% w/w phosphoric acid (acid-to-ash ratio), followed by a water-washing process with a liquid-to-solid ratio of 3:1 L/kg. This technique showed successful results and proved to be a promising solution for eliminating the risk of disposed ash (Vavva *et al.* 2020).

Supercritical fluid technique

Recently, supercritical fluid technologies, such as supercritical fluid extraction and supercritical water oxidation (SCWO), have emerged as potential approaches for the treatment of various wastes. SCWO is an environmentally friendly technology that utilizes the unique behavior of water under supercritical conditions ($T > 374.1$ C, $P > 22.1$ MPa).

Supercritical water is an excellent solvent for nonpolar hydrocarbons, that is, hydrocarbons, and converts them into water and carbon dioxide within a short residence time. SCWO has been used to treat various types of wastewater, that is, to remove pollutants from hospital wastewater (Sukandar *et al.* 2009), reduce the concentration of total organic compounds in olive oil mill wastewater (Top *et al.* 2020), and diminish the chemical oxygen demand (COD) from industrial dyeing wastewater (Erkonak *et al.* 2008; Gong *et al.* 2008; Top *et al.* 2020). SCWO is an effective method for municipal sludge treatment (Goto *et al.* 1997). To improve the oxidation results of supercritical water, strong oxidizers (pure oxygen and hydrogen peroxide) were used in the study by Bo *et al.* (2009), who found that after the SCWO treatment, a large portion of Ba, Cr, and Zn in the medical ash was transferred to the residual fraction. Cu and Pb were transformed into more stable complexes with organic matter. However, adding hydrogen peroxide to supercritical fluid (SCWH) stabilizes heavy metals in Fe–Mn oxides and residual fractions. These results indicate that treatment using SCW and SCWH is an effective method for stabilizing hazardous elements in MWA.

PCDDs and PCDFs in fly ash were decomposed using the SCWO technique, with a 99.7% maximum decomposition yield when hydrogen peroxide was added (Sako *et al.* 1997). Although SCWO technology is a promising solution for a wide range of organic wastewater, it has some technical drawbacks such as corrosion, salt precipitation, and high energy demand (Vadillo *et al.* 2013).

Cement-based technique

The cement-based technique (CST) is a treatment process that attempts to either stabilize the hazardous components by binding them into a stable and insoluble state or by solidifying the waste by entrapping it inside a solid cement matrix. The main objective of this technique is to reduce the solubility of contaminants and enhance the handling characteristics of the waste (Wiles 1987).

CST may contain many additives such as phosphate, silica, and ferrite solutions (Conner & Hoeffner 1998). According to Anastasiadou *et al.* (2012), the heavy metals in fly and bottom ashes were stabilized, and their percentages in the TCLP leachate were noticeably reduced after using the cement-based solidification method. This result agreed with results from other studies; for example, Lombardi *et al.* (1998) and Akyildiz *et al.* (2017) examined the leaching properties of MWA stabilized with cement and discovered that the combination of cement and ash reduced the level of heavy metal immobilization in incinerated MWA, and CST proved to be an effective pre-landfill waste treatment (Lombardi *et al.* 1998; Akyıldız *et al.* 2017). Supplementary Table 6 presents previous studies conducted on the stabilization of MWA using cement-based treatment, the operating conditions (cement–ash ratio and curing time), and their main findings.

The parameters that might affect the stabilization/solidification of waste ashes using cement (ash–cement ratio, additive type, and washing time) have mainly been investigated for municipal waste ashes (Fan *et al.* 2018). The disadvantages of cement solidification include the use of a large amount of cement and causing fly ash to expand by 1.5–2 times its original volume, which is problematic at landfill sites (Ma *et al.* 2019). Furthermore, the use of CST for solidification/stabilization is temporary concentration control, which cannot ensure long-term security and stability (Fan *et al.* 2018).

Melting technique

Because high-temperature procedures can easily degrade organic contaminants and effectively immobilize leachable heavy metals in melted slag, melting technology has become a widely popular method over the past decades. Compared to cement-based techniques, melting technology can successfully remove harmful organic compounds while reducing the volume of waste ash by 80% (Wang *et al.* 2010). Melting technologies include surface treatment, rotary kilns, and plasma melting. Melting technology is an energy-intensive method that requires large amounts of electricity (Ma *et al.* 2017). However, using melting technology, nonvolatile heavy metals are immobilized in a stable glass matrix, making the slag resistant to leaching (Wang *et al.* 2010).

Plasma arc treatment is a thermal treatment technique in which a direct-current (DC) hollow graphite cathode is inserted through the top of a furnace and supported by a vertical manipulator column. The inert gas, generally argon, creates a plasma arc that is transmitted to the furnace melt. Pan *et al.* (2013) confirmed that the DC arc plasma method could reduce Pb, Zn, Cr, Cu, and Cd leachability. The dioxins in MWFA were decomposed while reducing the volume of MWFA.

The main obstacle to using a melting treatment is the emission of high metal content, that is, Cr, Fe, Pb, Cu, Ni, and Zn (Jung Matsuto & Tanaka 2005; De Casa *et al.* 2007). Furthermore, the metal melting procedure releases a high level of chloride, which may cause corrosion of the melting furnace's refractory lines (Wang *et al.* 2010). This opens the floor for further investigations to find proper solutions to these problems.

Flotation technique

Flotation is a physicochemical technique commonly used for solid separation, particularly in primary mineral and chemical industries. The solid particles must have hydrophobic surfaces to float. The attachment of solid particles with hydrophobic surfaces to air bubbles is the basic principle of flotation techniques. The buoyancy of the bubble elevated the attached solid particles to the top of the flotation cell, where the fourth zone formed (Al-Thyabat & Al-Zoubi 2012; Al-Zoubi *et al.* 2015).

To make the surface of unwanted particles hydrophobic, collectors should be added, and other flotation agents should be added to the process to facilitate the attachment between the air bubbles and hydrophobic solids (Leja 1982). The frother is usually needed to create air bubbles in the flotation process. The operating parameters that would affect the flotation performance are the slurry (ashes and flotation agents) concentration, type and dosage of flotation agents (collectors and frother), airflow rate, and the particle size of ashes (Liu *et al.* 2013, 2020).

The carbon content of MWFA, including powder-activated carbon (PAC) and unburned carbon (UC), enriches fly ash with dioxins. UC is the main source of dioxins in MWFA through *de novo*, whereas PAC transfers dioxins to fly ash from flue gases by adsorption (Huang *et al.* 2007; Lu *et al.* 2013). The mechanism of dioxin removal using the flotation technique is based on the adsorption of dissolved dioxins by the hydrophobic PAC and UC. Air bubbles then capture and carry the mixture into the froth region on the top of the column, as shown in Figure 2. In several studies, the collector and frother were kerosene and methyl isobutyl carbonyl, respectively (Liu *et al.* 2013, 2019; Wei *et al.* 2018).

Supplementary Table 7 summarizes the studies conducted on MWA treatment using flotation techniques. The objectives of each study, the operating parameters, and the main findings are presented in this table, which shows that the removal efficiencies of dioxins and heavy metals using the flotation technique are relatively high.

Low operating costs, high efficiency in removing impurities, and short detention times are the advantages of flotation technology. However, flotation on an industrial scale is constrained by design and maintenance issues (Rubio *et al.* 2002; Bouchard *et al.* 2009).

Mechanochemical technique

The mechanochemical stabilization (MC) technique is a nonthermal approach in which mechanical forces (such as compression, collision, and friction) induce chemical reactions between solid particles (Chen *et al.* 2019). In mechanochemical treatments, four main reagents are employed: (1) reducing agents, including zero-valent metals (e.g., Mg, Zn, Fe, and Al) are applied with organic compounds as hydrogen donors, whereas hydrides serve as electron and hydrogen donors (Birke *et al.* 2004). (2) Lewis bases, such as CaO, MgO, La_2O_3, Al_2O_3, and Bi_2O_3. (3) Neutral species, which can generate free radicals to decontaminate organics, such as quartz and alumina. (4) Oxidizing agents, such as birnessite $(\delta - MnO_2)$ and persulfate $(S_2O_8^-)$ (Cagnetta *et al.* 2016).

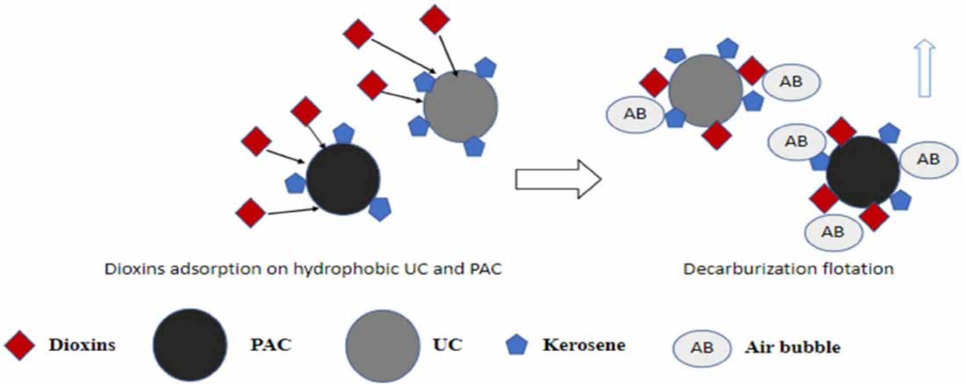

Figure 2 | Conceptual diagram of dioxin removal using flotation (Liu *et al.* 2020).

Mechanical energy is mainly used to crush solid particles, generate new surface areas, enhance the adsorption process, and improve chemical reactivity at ambient temperature (Geng *et al.* 2021). The degradation of chlorinated organic compounds is achieved by dechlorination or dehydrochlorination, leading to the formation of organic chlorides (Cagnetta *et al.* 2016). The efficiency of MC technology in destroying halogenated contaminants in contaminated waste, such as dioxins in MWFA, has been demonstrated. Peng *et al.* (2010) studied the degradation of PCDD/Fs using a mechanochemical technique without adding reagents. The degradation efficiency reached 76%, and the results showed that PCDD had a greater percentage reduction than PCDF. Yan *et al.* (2007) investigated the parameters that affect the degradation efficiency of PCDD/Fs using a mechanochemical technique. The tests in this study were performed using CaO to MWFA of 6, 12, 40, and 60% and rotational speeds of 350 and 400 rpm. The results revealed that the degradation efficiency of dioxins increases with an increase in the CaO ratio and rotation speed (see Supplementary Table 8).

The efficiency of mechanochemical techniques in stabilizing and suppressing the leaching of different heavy metals in municipal waste fly ash has been (Chen *et al.* 2019). Geng *et al.* (2023) confirmed that the MC process can efficiently stabilize the mercury in mercury-rich fly ash. However, the main drawbacks of the mechanochemical treatment of ash are the high energy consumption, high purchasing and installation costs of milling devices, and long milling times for specific reactions.

Microwave technique

Microwave treatment has many potential advantages over conventional thermal methods. These include selective and rapid heating and volumetric heating (Schulz *et al.* 2011). In conventional heating methods, heat diffuses from the surface toward the interior region. This is the reverse of the microwave heating process, in which the interior portion becomes hotter than the exterior surface (interior heating) (Remya & Lin 2011; Tyagi & Lo 2013).

Wei *et al.* (2017) investigated the possibility of using microwave treatment to decompose PCDD/Fs in the froths produced through the flotation of MWFA. The results indicated that the total mass destruction efficiency of dioxins in the froths was 99.6 wt.%. The decomposition of the PCDD/F mechanism mainly includes the generation of hot spots on the PAC surface due to microwave energy absorption. The rapid heating of PAC would decompose the dioxins into HCl, CO_2, and H_2O (Figure 3).

Supplementary Table 9 summarizes the advantages, drawbacks, and applicability of each treatment technique of MWA mentioned in the above sections.

APPLICATIONS OF MWA

Numerous studies have investigated the possibility of utilizing and recycling the ashes generated from hospital incinerators. For example, a recent study examined the option of using MWFA and MWBA instead of filler in asphalt mixture (Jaber *et al.* 2022). Slag results from melting hospital waste ash proved to be an efficient alternative aggregate for road construction (Azni *et al.* 2005). However, the primary concern of the applicant is the unexpected leaching of heavy metals into the soil and groundwater, resulting in an environmental problem.

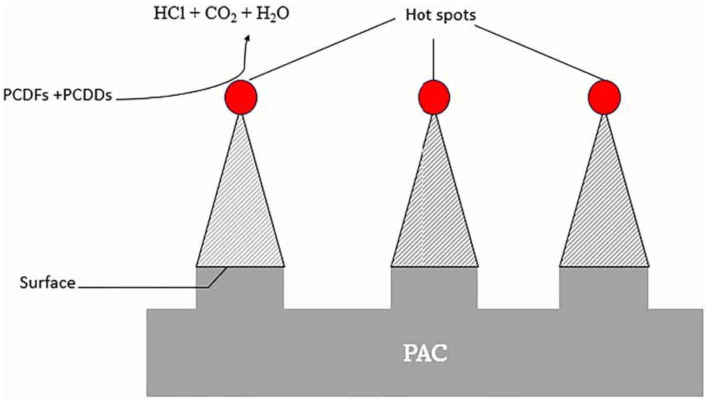

Figure 3 | The decomposition process of PCDD/Fs on the hot spots developed on the PAC surface during microwave treatment (Wei *et al.* 2017).

Other studies have found that MWA can be used as raw material in the production of geopolymer and its ability to increase the compressive strength of geopolymer matrices (Tzanakos *et al.* 2014). Geopolymers are promising candidates in various scientific fields, including physical chemistry, colloid chemistry, and geology. Furthermore, geopolymers have been explored in engineering applications, including ceramic cement, concrete production, and toxic radioactive waste treatment (Davidovits 2020).

As it contains nutrients, biomedical waste ash can be used as fertilizer in agriculture. The biomedical waste was used to boost the growth and yield of fenugreek and mustard, with promising results (Goswami-Giri 2007). The use of biomedical waste ash as fertilizer depends on the type of soil and crop used. Therefore, further investigations should be conducted to determine the influence of biomedical waste ash on the growth of different types of crops and to investigate its applicability on an industrial scale.

Several studies have highlighted the potential use of MWA as a partial replacement in concrete production. This is attributed to the presence of CaO and SiO_2 within MWA, in addition to the low cost and availability in sufficient amounts. Kaur *et al.* (2019) reported that using 5% incinerated MWA as a partial replacement improved the strength and durability of concrete, whereas beyond 10% replacement, the concrete strength properties were lowered, and up to 20% substitution decreased heavy metal immobilization. These results agree with those of Al-Mutairi *et al.* (2004), who reported that 5% fly MWA as a replacement enhanced the strength of concrete, whereas adding BMWA did not increase the strength of the concrete produced. Another study in India found that 7.5% is the optimum replacement level for incinerated biomedical waste ash in concrete mixtures, with a significant increase in compressive strength by 20%, split tensile strength by 17%, and flexible strength by 14% (Katare *et al.* 2022).

Ababneh *et al.* (2020) also investigated the possibility of recycling treated MWFA in a mortar mixture. Three sets of mixes with different mix proportions were prepared; in the first set, the mortar mix was made with a ratio of 1 kg:2.75 kg:550 ml for cement: sand:water, respectively. In the second set, the cement was mixed with 0.5% silica nanoparticles. In the final set, the original MWFA and treated MWFA were added as a partial replacement for cement, with percentages ranging from 0 to 20% of the cement weight. The results indicated that the replacement of MWFA achieved acceptable flexural and compressive strengths.

Another recent study by Matalkah (2023) used 40% replacement of MWBA in a concrete mixture combined with different activation methods to enhance the compressive strength of the concentrate produced, such as dry ball milling, wet milling, calcination, and wet milling followed by calcination. The results show that both dry and wet milling increased the ash reactivity and compressive strength of ash by 20%. Calcination alone improved the compressive strength by >35%. The greatest compressive strength was obtained from wet milling, followed by calcination. More details about the utilization of MWA in different industries are highlighted in Supplementary Table 10.

Cement production is responsible for significant energy consumption and the release of large amounts of CO_2 into the atmosphere, which is a primary contributor to global warming. Utilizing MWA in the cement sector offers the notable advantage of reducing CO_2 emissions. This results from the fact that medical waste, which is composed of lime (CaO) instead of $CaCO_3$, contributes to a decrease in carbon dioxide emissions. However, the adoption of MWA on an industrial scale presents various technical challenges. The high chloride levels present in the ash can negatively impact cement quality, along with a notable concentration of heavy metals. Pretreatment of MWA before its application in cement production is required to reduce its chloride and heavy metal contents. In addition, the addition of medical waste ashes during the production process should be carefully controlled to ensure both process safety and cement quality.

CONCLUDING REMARKS AND FUTURE RESEARCH DIRECTIONS

The hospital waste incineration products are classified into fly ash (MWFA) and bottom ash (MWBA). Both types of ash contain high amounts of heavy metals, whereas MWFA contains a high amount of PCDD/Fs. Several leaching test results have also shown that heavy metals in medical waste ashes have high affinity and may threaten the environment. Thus, different treatment techniques have been investigated to minimize the toxicity and solubility of these hazardous substances, such as mechanochemical, melting technique, microwave technique, flotation, chemical, and cement-based techniques. Recycling and utilizing MWA in agriculture, geopolymers, cement, and asphalt production have shown promising results. Future studies should focus on the treatment techniques for medical waste ashes and attempt to overcome the shortcomings of the available methods. In addition, it is necessary to identify other application areas that can utilize the ash generated from the hospital incinerator.

1. The treatment of hospital waste ash has rarely been specifically studied; therefore, further investigations should be conducted to study the applicability of some treatment techniques.
2. Improve control techniques to ensure the stable operation of high-temperature treatment techniques.
3. Further studies and improvements in melting treatment techniques are required to reduce the emissions of chlorine and metals.
4. Further investigations should be conducted on the long-term leaching properties of cement-based techniques.
5. Further studies on the flotation process are required to resolve the industrial scale problems.
6. Find other methods to utilize the ashes generated from hospital waste incineration.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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