Journal of Air Pollution and Health (Autumn 2021); 6(4): 287-334

Review Article

Available online at http://japh.tums.ac.ir

Incineration of medical waste: Emission of pollutants into the environment

Samaneh Taghilou[1,2], *Javad Torkashvand*[1,2], *Majid Kermani*[1,2,*], *Mahdi Farzadkia*[1,2]

[1] Research Center for Environmental Health Technology, Iran University of Medical Sciences, Tehran, Iran
[2] Department of Environmental Health Engineering, School of Public Health, Iran University of Medical Sciences, Tehran, Iran

ARTICLE INFORMATION

Article Chronology:
Received 10 October 2021
Revised 20 November 2021
Accepted 12 December 2021
Published 30 December 2021

Keywords:
Medical waste; Incineration; Waste management; Air pollution

CORRESPONDING AUTHOR:

majidkermani@yahoo.com
Tel : (+98 21) 86704768-88622618
Fax : (+98 21) 88622618

ABSTRACT

Medical waste incinerator is a matter of concern for the environment and public health due to secondary pollutants. The present work aims to evaluate the toxic emissions from medical waste incineration, such as Polychlorinated Dibenzo-Dioxin/Furan (PCDD/Fs), Polycyclic Aromatic Hydrocarbons (PAHs), and the inorganic components in ambient air and ash. Hence, this study discusses several strategies to reduce emissions. For this purpose, searches were done in Scopus, Web of Science, and PubMed databases from 2000 to 2020. After the search, screening was done according to the predefined criteria, 96 papers were finally selected for this study. The results show that the emissions levels depend on many factors like the composition of the feeding, waste type, waste classification, segregation practice, types of incinerators, operation conditions (designed temperature, retention time, and excess oxygen), and air pollution control devices. For instance, emissions of Medical Waste Incinerators (MWIs) rise sharply with a decrease in temperature, increase in oxygen levels and chlorine content in waste, and the absence or weak function of air pollution control systems. This review prepared a comprehensive detailed for decision-makers to help them to understand the environmental consequences of using incinerators. However, there is a gap in finding efficient methods to reduce emissions of incinerators.

Review

The healthcare centers present services like caring, therapy, and enhancement of the quality of life, which plays a major role in human's social life among the other welfare services in the world. Healthcare organizations are responsible for giving equal, fair, on time, available, sufficient, generative, and high-quality services to the people and patients according to their rights [1].

Healthcare wastes have been rose in recent decades due to the population growth, increase in healthcare center's count and size, using disposable medical products, and daily-growing attention to clinical services worldwide [2, 3]. Hospital waste is defined as any solid wastes resulting from diagnosis, treatment, or immunization of humans or animals in research, clinical, and veterinary centers, as well in medical labs [4, 5]. Medical waste contains infectious agents, toxic chemical matters, and heavy metals

Please cite this article as: Taghilou S, Torkashvand J, Kermani M, Farzadkia M. Incineration of medical waste: Emission of pollutants into the environment. Journal of Air Pollution and Health. 2021; 6(4): 287-334.

and may contain geo-toxic and radioactive compounds [2]. Some types of these wastes are more harmful than the other type. Almost 15-25% of these wastes are assumed infectious. The World Health Organization (WHO) has estimated that injections using the infected syringes are responsible for 21 million people infected by hepatitis B, 2 million by hepatitis C, and 260 million by the Human Immunodeficiency Virus (HIV). On average, medical waste components comprise syringes, gloves, bandage tapes, and cotton [6]. The amount of the generated waste depends on various factors like the healthcare installations type, specialties, percent of reusable goods, percent of patients under treatment per day, and the type of the presented health services. Inspecting the waste of the 35 hospitals showed that the major part of the daily-generated wastes contains the general wastes (food waste and hospital cleaning), paper, glass, and plastics [7]. About 650,000 tons of medical waste is produced annually by the country's health system. The quantity of this waste type is growing rapidly with a 20% annual rate [8].

However, medical services are vital to have a healthy life, but mismanagement of medical wastes directly affects human health and damages ecosystems comprising plants and animals [7]. These wastes may lead to infection for the patients in every hospital and its crew. On the other hand, financial resources are usually inadequate for waste management. The number of crew workers in healthcare services is few in such countries, and most of the time, they are not educated enough to deal with the wastes properly and manage them [9]. Medical wastes in developing countries are a serious issue due to unsuitable treatment and disposal. These deficiencies give a bolder role to the appropriate treatment and disposal approaches of wastes [10, 11]. There are many techniques for treatments and disposal of medical wastes, such as steam sterilization, chemical disinfection, ionizing radiation, microwaving, recycling, incineration, and biological systems like enzymes [12, 13].

There are also incineration methods for medical wastes like dual-chamber air-controlled incinerators, multiple chamber incinerators, rotary kilns incinerators, cement incinerators, the fluidized furnace combustion technique, combustion with energy recovery, and pyrolysis incinerators [14-16]. Incineration has been used widely for hospital waste disposal [17] due to its advantages like reducing the mass of waste more than 70 wt% [18] and volume of waste around 90% [19], destruction of toxic and infectious organic components, and the feasibility for heat recovery or electricity [16, 20]. On the other hand, the potential toxic gaseous emission, high operation, and maintenance costs, and disposal of residual ash are the main disadvantages of this method [21-24]. The emitted pollutants of uncontrolled incinerators are carbon dioxide, particulate matter, carbon monoxide, nitrogen oxides, sulfur dioxide, heavy metals (cadmium, mercury, lead, arsenic, chrome, manganese, nickel), furans (PCDFs), dioxins (PCDDs), chlorinated compounds including Polycyclic Aromatic Hydrocarbons (PAHs), Poly Chlorinated Biphenyls (PCBs), phosphorus pentoxide, hydrogen cyanide, Hydrogen Chloride (HCl), hydrogen sulfide, Hydrogen Fluoride (HF), carbonyl compounds like formaldehyde and Volatile Organic Compounds (VOCs) like benzene, toluene, styrene and xylene [23, 25-27].

The process of medical waste incineration produced ashes by 35% [28]. Fly ash and bottom ash released from medical waste incineration contain high levels of toxic organic pollutants (dioxins, furans, and PAHs), leachable alkali chlorides [29], and heavy metals (Cu, P b, Zn, As, Cd, Cr, Hg, Ba, Mn, Ni, and Sn). Bottom ash has fewer amounts of pollutants than fly ash and hence

is concerned to be safer [30]. Because of the mentioned reasons, fly ash coming from flue gas control systems are classified as dangerous waste with code 19.01.13, while bottom ash was included in 2003 on the dangerous waste according to the council of European Union [31]. Leaching concentrations for the majority of heavy metals exceed the standard limit for hazardous waste landfills. So, it needs prior treatment. The metals in this kind of waste are not biodegradable and could easily penetrate the soil, reach underground waters, pollute the environment and cause harm to human beings [29].

This study has systematically reviewed reports of toxic emissions from medical waste combustion into air and ashes like Polychlorinated Dibenzo-Dioxin/Furan (PCDD/Fs), PAHs, inorganic compounds, and heavy metals. The main applicable factors in reducing the emissions are as well discussed. Presenting a complete set of information about the emissions of incinerators will be beneficial for decision-making and reveal the research's challenges and requirements.

Search of literature

PubMed, Web of Science, and Scopus databases were searched to find related studies around the medical waste incinerators. Meanwhile, the search protocol is used as follows:

((TITLE ("medical waste") OR TITLE ("hospital waste") OR TITLE ("infectious waste") OR TITLE ("healthcare waste") OR TITLE ("health-care waste"))) AND ((TITLE-ABS KEY (incineration) OR TITLE-ABS-KEY (combustion) OR TITLE-ABS-KEY (pyrolysis)))

This search protocol was used to identify publications from 01 January 2000 to 24 October 2020.

Eligibility criteria

The final papers have been selected based on eligibility criteria. This study has focused on those studies that investigated medical waste incinerators. Therefore, all of the documents that mentioned 1) emissions from medical waste incineration, 2) specified pollutants emitted from incinerators, 3) sources of emissions that were also involved in the incineration of medical waste, 4) emissions from medical waste incinerators in different conditions, and 5) spatiotemporal distribution of incinerators emission in ash and atmospheric air were selected.

Study selection

According to the criteria mentioned above, the literature was screened independently by every author. After an initial screening of the titles, 265 studies were selected. The respective research was included in the next step of screening in the case of conflicting decisions over the initial screening. Two hundred twenty studies were selected by the abstract that 111 papers investigated emissions in the air, 100 papers investigated pollutants in the ashes, and nine papers referred to both of them. Eventually, the contents of the articles were studied, and 96 papers (Fifty-seven in the air and thirty-nine in the residuals of incineration) were selected, which were rich in comprehensive information about the amount and synthesis of incinerators' emissions (Fig. 1).

Literature review

Investigation of studies illustrated that the main emissions are dioxins, furans, PAHs, and heavy metals presented in Table 1 and ashes (Table 2).

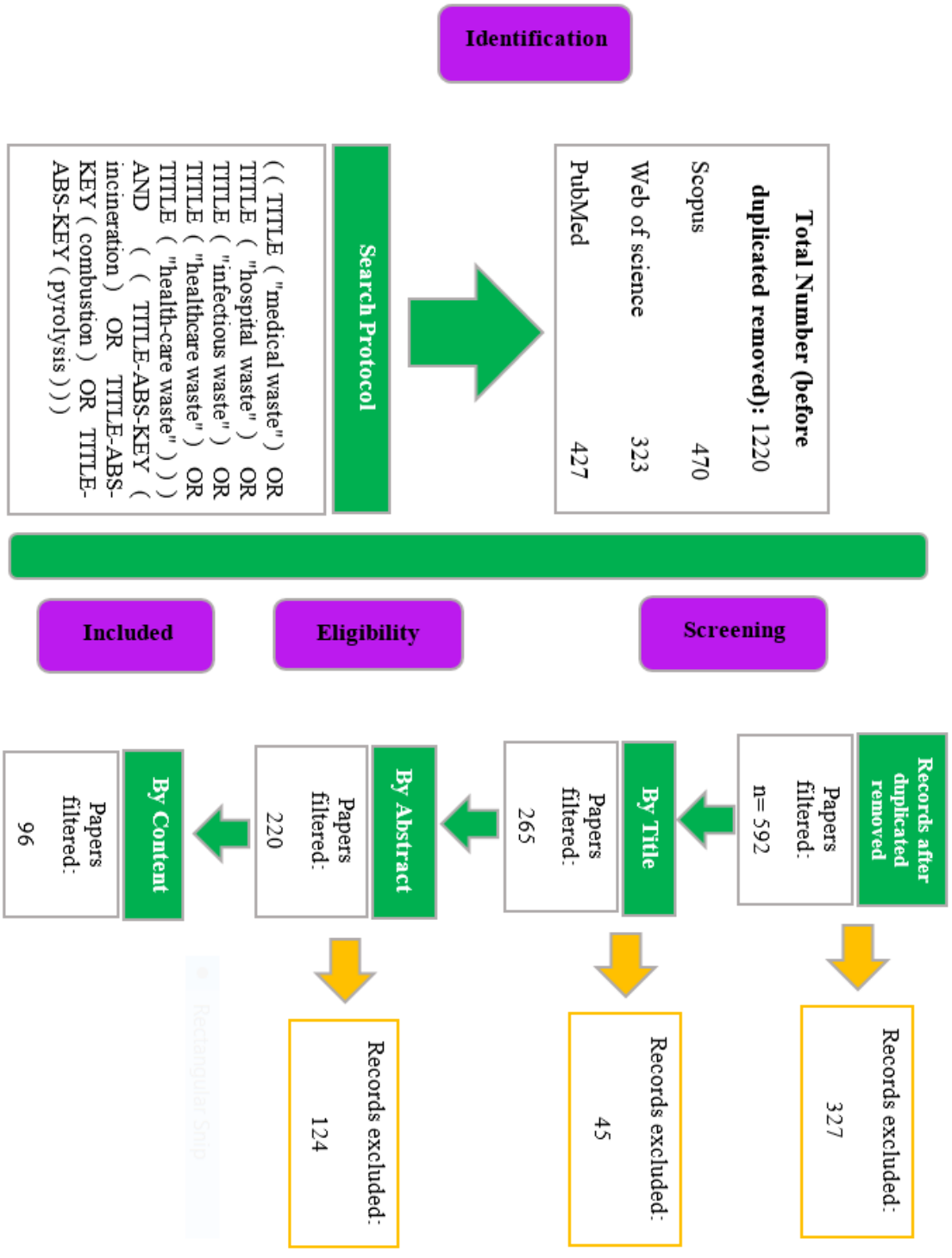


Fig. 1. Flow diagram describing the paper selection procedure through the different stages of this systematic review

Table 1. Concentration of pollutants emitted from the stack of medical waste incinerators to air

Country	Facility type	Operation conditions	Studied pollutants	APCDs	Year	Remarks	Ref.
Taiwan	Rotary kiln incinerator	First incinerator chamber (including 2.5 s retention in 1041 ^{0}C rotary kiln, and over 5 s retention in the 900±50 ^{0}C rotational-fluidized bed incinerator)	$PM_{2.5}$, PM_{10} PAHs, Benzo(a)pyrene	Water-cooled quenching tower, heat exchanger, baghouse	2007	- The concentration of $PM_{2.5}$ and PM_{10} in the study area was 29.05 ± 13.30 and 35.27±14.18 ng/m^3. - Concentration of total PAHs in PM_{10} in the study area (distance 1 km) was 0.83±0.68 ng/m^3, while in the reference area (distance 11 km) was 0.64±0.34 ng/m^3. - Concentration of particles in the study area in the downwind was significantly higher than in the upwind. - Concentration of PAHs in $PM_{2.5}$ in the study area is 2.2 times higher than the reference area.	[32]
Poland	Uncontrolled open burning incinerator	-	PAHs, Carbonyl compounds	NO	2009	- Concentration of total carbonyl compounds was 353.167 µg/m^3. - Concentration of total PAHs was 235.758 ng/m^3. - The highest total concentrations of aldehydes and ketones were obtained in medical waste incinerators due to the high concentration of formaldehyde (251 µg/m^3) in the collected samples.	[27]
Egypt	Batch type incinerator	- Using light oil as auxiliary fuel, except No. 6 which was using kerosene. -Incineration period: 3 to 4 hours most of the time once a day, except No. 1, where	Smoke, Lead, CO, SO_2, NO_2	Incinerator No. 1 no control, No.5 mostly had primitive control, the other five incinerators had a scrubber	2005	- Concentrations of air pollutants in six incinerators for CO, NO_2, SO_2, smoke, and lead were 170-4100, 6-340, 8-4310, 25.4-2110 mgm^{-3}, and 23.5-322.8 µg/m^3, respectively. - The average amount of gases in six incinerators was in the range of Egyptian environmental law. And only	[33]

Table 1. Concentration of pollutants emitted from the stack of medical waste incinerators to air

Country	Facility type	Operation conditions	Studied pollutants	APCDs	Year	Remarks	Ref.
		incineration was twice daily. - Incinerators had two burners except incinerator No. 5 which had only one.				the average of smoke in six incinerators was higher than the allowable limit in this law. - Lead concentration was much lower than the maximum allowable under this law. Emissions of the No.6 incinerator were significantly higher than those of the others in the case of CO, NO_2, SO_2 and smoke.	
USA	Dual-chamber controlled–air incinerators or pyrolytic incinerators	The gas residence time of 2 s, exhaust temperature of up to 1025°C	Black carbon (Smoke)	NO	2016	- Significantly less smoke is emitted during the combustion of cardboard containers (6.81 ± 4.79% smoke) than plastic containers (17.77 ± 8.38% smoke). -The average black carbon emitted during the combustion of plastic containers is 2.61 times higher than cardboard containers.	[15]
UK	State-of-the-art incinerator	Secondary combustion chamber operated at 800–1000°C with 10% O_2	PAHs, PCDDs, Cd, As, Cr, Ni	Cyclone and lime scrubber followed by an array of ceramic filters	2010	- The concentrations of PAHs (as BaP), PCDDs (as TEQ), Cd, As, Cr (VI), and Ni were 7.4, 0.37, 2.2, 3.5, 22.4 and 65.9 ng/s, respectively.	[34]
South Korea	Traveling-grate stoker OR fixed-grate stoker incinerator	The regular maintenance period of about 30 days annually, operate without shutdown	PCDD/PCDF	Each incinerator used at least three or more of these: cyclone, semi-dry reactor, and wet scrubber, activated carbon, bag filter, multi-cyclone, spray dryer absorber	2017	- The mean concentration of PCDD/PCDF was 0.153-101.9 ng/Sm^3. - Between the 19 studied incinerators, the four exceeded the emission standards. - Incinerator type/operation, capacity, APCDs, and start-up date were not significantly associated with high concentrations of PCDDs/PCDFs in this study.	[3]

Table 1. Concentration of pollutants emitted from the stack of medical waste incinerators to air

Country	Facility type	Operation conditions	Studied pollutants	APCDs	Year	Remarks	Ref.
Russia	Pyrolysis and Incineration	de novo mechanism, surface-mediated *precursor's* mechanism, *homogeneous* gas-phase mechanism	PCDD/PCDF	NO	2019	- In direct incineration conditions, the concentration of PCDD/Fs was more than twice the concentration obtained under pyrolysis. - In both methods, the concentration of dibenzofurans was higher than the concentration of dioxins. -The formation of PCDD/Fs based on the mechanisms mentioned in the operation conditions occurs at a temperature of 250-400 °C, 200-500 °C, and 600-800 °C, respectively.	[35]
China	Hazardous waste incinerator with electricity generation	Without energy Recovery, Energy recovery efficiency 15% and 30%	Dioxins	Wet scrubber, Electrostatic precipitator, DeNOx reduction stage	2008	- The concentration of dioxin measured as TEQ is 3 ng/kg.	[16]
Portugal	Classic incineration	-	Dioxins, Cd, Hg, Pb, Cr (total), Cr (VI), Fe, Mn, Ni, As, CO, NO_2, SO_2, Particles, HCl (as Cl^-), Benzene	NO OR Fabric Filter/Dry Scrubber, Wet Scrubber	2000	- The amount of emission pollutants without control of pollutants in case of incineration 40% of waste for Dioxins, Cd, Hg, Pb, Cr (total), Cr (VI), Fe, Mn, Ni, As, CO, NO_2, SO_2, PM, HCl (as Cl^-) and Benzene were 0.018, 1.1, 14, 16, 0.23, 0.018, 2.7, 0.14, 0.069, 0.065, 1400, 1100, 310, 1700, 6000 and 0.73 kg/yr, respectively. - And when 60% of the waste was incinerated, the values were 0.026, 1.7, 21, 24, 0.35, 0.026, 4, 0.2, 0.1, 0.098, 2100, 1700, 470, 2600, 9100 and 1.1 kg/yr, respectively.	[36]

Table 1. Concentration of pollutants emitted from the stack of medical waste incinerators to air

Country	Facility type	Operation conditions	Studied pollutants	APCDs	Year	Remarks	Ref.
						-If there was no control on air pollutants, incinerators did not obey the standard emissions limit.	
China	Medical waste incinerator	-	PCDD/PCDF	-	In the winter 2015-2018	- The PCDD/PCDF concentration as I-TEQ was 0.542-21.3 ng/Nm^3.	[37]
Portugal	Controlled air incinerator	Correct practices of maintenance and operation	Dioxins	NO	2003	- Concentrations of dioxins as I-TEQ for different scenarios include [1]INCM, -INCIV[4]USUSeg and -INCIV[3]INCIII, [2] RIGseg were 320, 250, 13, and 2 mg/yr, respectively.	[4]
China	Starved-air incinerator	Two furnace chambers, the first chamber temperature (350–550 °C)	PCDDs, PCDFs	Quench scrubber, Semi-dry scrubber, Fixed absorber filled with activated carbon, Baghouse filter	2015	- Released values for shutdown and start-up conditions were 483±184 ng/Nm^3 (1.47±0.17 ngI-TEQ/Nm^3) and 735 ng/Nm^3 (7.73 ngI-TEQ/Nm^3), respectively. - The mean concentration (I-TEQ) during shutdown and start-up was 2.6 (3.8) and 4 (approximately 20) times higher than the during normal operation, respectively.	[38]
China	Rotary kiln	Retention time and temperature in the kiln: 40~73 min and 750–850 °C, in secondary combustion: >2 S and 917~1193 °C	PCDD/F	Acid scrubber, Activated carbon chamber, Baghouse filter, Alkaline scrubber	2015	- The concentrations of PCDD/F in flue gas was 17.7 ng(I-TEQ)/Nm^3.	[39]

[1] INCMIX: incineration of the following mixture: groups I and II, 36.3%; group III, 51.0%; group IV, 12.7% (60% of the total groups I and II and the total amount of groups III and IV)
[2] INCIII: incineration of group III
[3] INCIV-USUSeg: incineration of group IV using the usual segregation practice
[4] INCIV-RIGseg: incineration of group IV using the rigorous segregation practice

Table 1. Concentration of pollutants emitted from the stack of medical waste incinerators to air

Country	Facility type	Operation conditions	Studied pollutants	APCDs	Year	Remarks	Ref.
China	Rotary kiln, followed by burnout in a fluidized bed	-	PCDD/PCDF	Semi-dry scrubber and a fabric filter	2010	- The concentrations of PCDDs and PCDFs emitted from the stack before the air pollution control equipment were 0.08-0.44 and 0.61-5.25 μg/Nm^3, respectively. -The optimum temperature for CBz formation is in the range of 350-400 °C, and the yield of CBz increases significantly with oxygen linearly with the formation of PCDD/Fs.	[40]
China	Medical waste incinerator	-	PCDD/Fs	-	2016	- The concentration of total PCDD/Fs emitted from the flue gas was 0.516-122.803 ng/Nm^3.	[21]
Taiwan	Batch-type MWIs, including the one with a mechanical (MG-MWI) and the other with a fixed grate (FG-MWI)	MG-MW: Temperature of the first and second chamber 750–1000 ˚C and 1000–1200 ˚C, detention time (min/batch): 272 for FG-MWI: 700–1000 ˚C and 1000–1200 ˚C, 293 min/batch, respectively	PAHs	Electrostatic precipitator, wet scrubber	2001	- The mean concentration of total PAHs in the flue gas for MG-MWI (= 1290 mg/Nm^3) was 2.85 times higher than FG-MWI (= 587 mg/Nm^3).	[5]
Malaysia	Medical waste incinerator	Capacity: 650 kg/h (max), Auxiliary fuel: natural gas, temperature of the stack: 22 (˚C)	PM, NO_2, SO_2, CO, HCl, Cd, Pb, Hg	ESP, Fabric filters + Wet scrubber (limestone)	2016	- Emission concentration from stack for PM, NO_2, SO_2, CO, HCl, Cd, Pb and Hg were 85.67±41.04, 44.67±22.03, <3.0±0, 37.43±19.38, 0.13±0.04, 0.01±0.006, 0.03±0.01 and 0.04±0 mg/Nm^3, respectively.	[20]

Table 1. Concentration of pollutants emitted from the stack of medical waste incinerators to air

Country	Facility type	Operation conditions	Studied pollutants	APCDs	Year	Remarks	Ref.
						- The concentration of pollutants released from the stack was less than the limit set by the Environmental Quality (Clean Air) Regulation 2014. - Comparison of pollutants in the ambient air with the Recommended Malaysia Ambient Air Quality Guideline (RMAAQG) showed that the pollutants are acceptable for human and environmental exposure.	
Turkey	Two-stage combustion system consisting of a rotary kiln and a vertical shaft	Capacity: 35000 tons per year, exit gas temperature: 55 ˚C	PCDD/F	Electrostatic precipitator (ESP), Two-stage venturi scrubber, Activated carbon unit	2004	- The maximum annual concentration of PCDD/F in ambient air was 0.28 fg/ m^3 at 1480 m northeast of the stack.	[41]
Kenya	Kenyatta National Hospital (three chambers), Nairobi and Moi Teaching and Referral Hospital (two chambers)	KNH: mean stack temperature 746 °C MTRH: mean stack temperature 811 °C	SO_2, NO, NO_2	Condensate tank, Filter, Integrated electrochemical measuring cells	2012	- SO_2 concentrations of flue gas in KNH and MTRH were equal to 45.7 mg/m^3 and 159.4 mg/m^3, respectively, which is less than the standard limit in the former due to the consumption of diesel fuel with ultra-low sulfur. -The concentration of NO (104.1 mg/m^3) and NO_2 (0.4 mg/m^3) in KNH was lower than the standard limit, and in the case of MTRH, the NO concentration (604.8 mg/m^3) exceeded the limit and NO_2 (0.4 mg/m^3) obeyed the limit.	[13]
Portugal	Hospital waste incinerator	HAS: operated 416 hyr^{-1}, Stack	PCDD/PCDF	NO	2005	- The levels of gases emitted in HSA Hospital were 10 to 60 times higher than the European standard, and the amount	[42]

Table 1. Concentration of pollutants emitted from the stack of medical waste incinerators to air

Country	Facility type	Operation conditions	Studied pollutants	APCDs	Year	Remarks	Ref.
		temperature: 435, 430 °C HSJ: operation 4800 hyr^{-1}, Stack temperature: 185, 191 °C				of emissions in HSJ Hospital was three times higher. - HSJ operated for 416 h/yr (compared to a few hours for HSA) and is the main cause of dioxins and furans emission in Porto atmosphere with a total of about 200-400 mg I-TEQ/yr.	
Taiwan	Batch-type MWIs	MG-MWI: feeding rate ~1049 kg/batch, detention time 272 min, first and second chamber temperature 750-1000 °C and 1000–1200 °C with a retention time >2 sec FGMWI: ~144 kg/batch, 293 min, 700-1000 °C and second one as the same MG-MWI	PAHs	Electrostatic precipitator and a wet scrubber	2003	- Total PAHs for MG-MWI (1510 $\mu g/m^3$) were higher than FG-MWI (707 $\mu g/m^3$). - The APH released from both incinerators into the environment was not significant when APCDs were used during the incineration process.	[23]
Portugal	Controlled air incinerator	Capacity: 2×180 kg/h, residence time and the incineration temperature according to legislation	CO, SO_2, NO_x, HCl	NO	January-December 1999	- Concentrations of CO, SO_2, NO_x, and HCl released from the incineration of INCMIX-spec were 650, 89.8, 144, and 1360 mg/m^3, respectively. -The limit for NO_x was obeyed, but for CO (11-24 times), SO_2 (2-5 times), and HCl (9-200 times) were higher than the allowable limit.	[25]
Portugal	Controlled air incinerator	Capacity: 2×180 kg/h, temperature of primary and secondary	PM, As, Cd, Cr, Pb, Mn, Hg, Ni	NO	January-December 1999	- The concentrations of PM, As, Cd, Cr, Pb, Mn, Hg and Ni released from incineration of INCMIX-spec were 422,	[10]

Table 1. Concentration of pollutants emitted from the stack of medical waste incinerators to air

Country	Facility type	Operation conditions	Studied pollutants	APCDs	Year	Remarks	Ref.
		chambers: 890 and 1100 °C				0.00809, 0.194, 0.0573, 3.19, 0.0616, 5.67 and 0.0137 mg/m^3, respectively. Concentrations of PM, mercury (1.3-226 times), cadmium, and total metal concentrations (3 to 8 times) exceeded the limit.	
Portugal	Controlled-air incinerator	Correct practices of maintenance and operation	PM, Dioxins, As, Cd, Cr, Pb, Mn, Hg, Ni, CO, SO2, NOx, HCl	NO	1999	-The allowable limit only for NO_x obeyed. All other levels were higher than the maximum allowable limit: PM, Cd, dioxins (710-93 times), mercury (1.3-226 times), CO (11-24 times), SO_2 (2-5 times), and HCl (9-200 times) and the total concentration of metals (3-8 times).	[22]
South Korea	Starved air incinerator	Secondary chamber: 850 ˚C and at least 2 s of retention time of flue gas	PCDD/PCDF	Cyclones, Semi-dry scrubbers, Baghouse filters	2003, 2004	- The average concentrations of dioxins and furans were 9.23 ng-TEQ/Nm^3 in 2003 and 6.85 ng-TEQ/Nm^3 in 2004. -The average concentration level was exceeded the new standard.	[24]
India	Biomedical waste incinerator	-	NO_x, HCl, PM	Venturi	2016	- The concentrations of pollutants released from the stack for NO_x, HCl, and PM were 17.8, 75.8, and 196.2 mg/Nm^3, respectively. -NO_x levels in the range of standard and two other pollutants exceeded the standard.	[43]
China	Rotary kiln	-	PCDD/PCDF	INC_1: quench system, semi-dry scrubber, activated carbon, fabric filter	2013	- The mean concentrations for medical waste incinerators 1 and 2 were 0.45 and 1.33 ng I-TEQ/Nm^3, respectively. - Incinerator 1 obeyed emission standards, but incinerator 2 did not, which was due to weak APCSs.	[44]

Table 1. Concentration of pollutants emitted from the stack of medical waste incinerators to air

Country	Facility type	Operation conditions	Studied pollutants	APCDs	Year	Remarks	Ref.
				INC_2: semi-dry scrubber, fabric filter			
Nigeria	Rotary Kiln-type incinerator	Operating temperature range from 500 to 1100 °C	PAHs, as Alkyl-naphthalene	Flue gas scrubbers	June 2014– May 2015	- Emitted Alkyl-naphthalene from the stack was 0–14.0 ng/m^3. The mean monthly concentrations (Σalkyl-naphthalene) were 67.4±24.3 ng/m^3.	[45]
China	Rotary kiln and fluidized bed	Activated carbon injected into the flue gas except for condition1, more activated carbon was used for condition4.	PAHs, as PCBs	Fluidized bed, Cyclone, Quencher, Semi-dry lime scrubber, Bag filter	2009	- The total concentration of PCBs in the flue gas under different operating conditions ranged from 138.01-3192.75 ng/Nm^3.	[26]
Nigeria	Rotary kiln-type incinerator	Operating temperature 500 to 1100 °C	PAHs	Flue gas scrubbers	June 2014-May 2015	- The concentration of PAH emitted from the stack was in the range of NA up to 10.9 ng/m^3.	[46]
China	H1-3, 9-11: Pyrolysis + shaft kiln H4,8,12: Rotary kiln H5-7,14: Pyrolysis + rotary kiln H13: Pyrolysis	Stack temperature (°C) H1-H14, respectively: 100, 120, 110, 150, 130, 170, 150, 130, 150, 170, 190, 165, 170 , 150	PCDD/PCDF	H1-3,7, 9-11,13: semi-dry scrubber + activated carbon + fabric filter H4-6,8,12,14: semi-dry scrubber + fabric filter	2009	- Concentrations of incinerators 1 to 14 (I-TEQ ng/Nm^3) were 0.32, 0.22, 3.58, 0.50, 1.15, 2.81, 0.50, 0.20, 0.19, 0.19, 17.67, 0.08, 0.10 and 31.60, respectively. -Nine incinerators had emission levels below the Chinese standard and only two ones were below the European standard.	[47]
China	Pyrolysis Gasifier incinerator	-	PCDD/PCDF	Semi-dry scrubber, Activated carbon, Bag filter	2011	- The concentration of PCDD/PCDF in flue gas was 0.306 ng/ton waste. -The concentration of the stack was lower than the standard limit.	[48]

Table 1. Concentration of pollutants emitted from the stack of medical waste incinerators to air

Country	Facility type	Operation conditions	Studied pollutants	APCDs	Year	Remarks	Ref.
Poland	Rotary kiln with co-current combustion	Residence time of the flue gas: 2.5 s, Average temperature in beginning, end, and afterburner chamber: 902, 1039, and 1157 °C	Total dust, TOC, HCl, HF, SO_2, CO_2, NO_2	Multisectional bag filter	2015	- Concentration of pollutants in the flue gas for Total dust, TOC, HCl, HF, SO_2, CO, NO_2 were 0-63.4, 0-22.5, 1.88-37.52, 0-0.83, 0-337.8, 0-887.5 and 6.4-229.5 mg/Nm^3, respectively. -The concentration of the samples did not exceed the permissible limits.	[49]
Colombia	MWI-1,4,6,8: single-chamber INC MWI-3,5,7,9: double-chamber pyrolytic INC MWI-2,10,11,12: double-chamber excess air INC	Stack temperature (°C) for MWI-1,4,6,8: 639, 260, 400, 383 for MWI-3,5,7,9: 651.0, 119.4, 59.5, 186.9 for MWI-2,10,11,12: 521, 267, 431, 397	PM, PCCD/PCDF	MWI-1,4,6,8: NO MWI-3,5,7,9: Three out of four incinerators have a cyclone, and just one has a gas cooling system MWI-2,10,11,12: Only one out of four incinerators has a gas cooling system	2008	- Concentrations of PM (mg/Nm^3) and PCCD/PCDF (ng I-TEQ/Nm^3) emitted in MWI-1 were: 43.2 and 13.0, MWI-4: 157 and 16.5, MWI-6: 1170.6 and 263.8, MWI-8: 16.6 and 22.9, MWI-3: 123.2 and 50.6, MWI-5: 1550 and 708.5, MWI-7: 1084 and 156.8, MWI-9: 39.9 and 27.5, MWI-2: 162.4 and 17.0, MWI-10: 412.2 and 7.2, MWI-11: 318.1 and 166.4, MWI-12: 468 and 557.8, respectively.	[50]

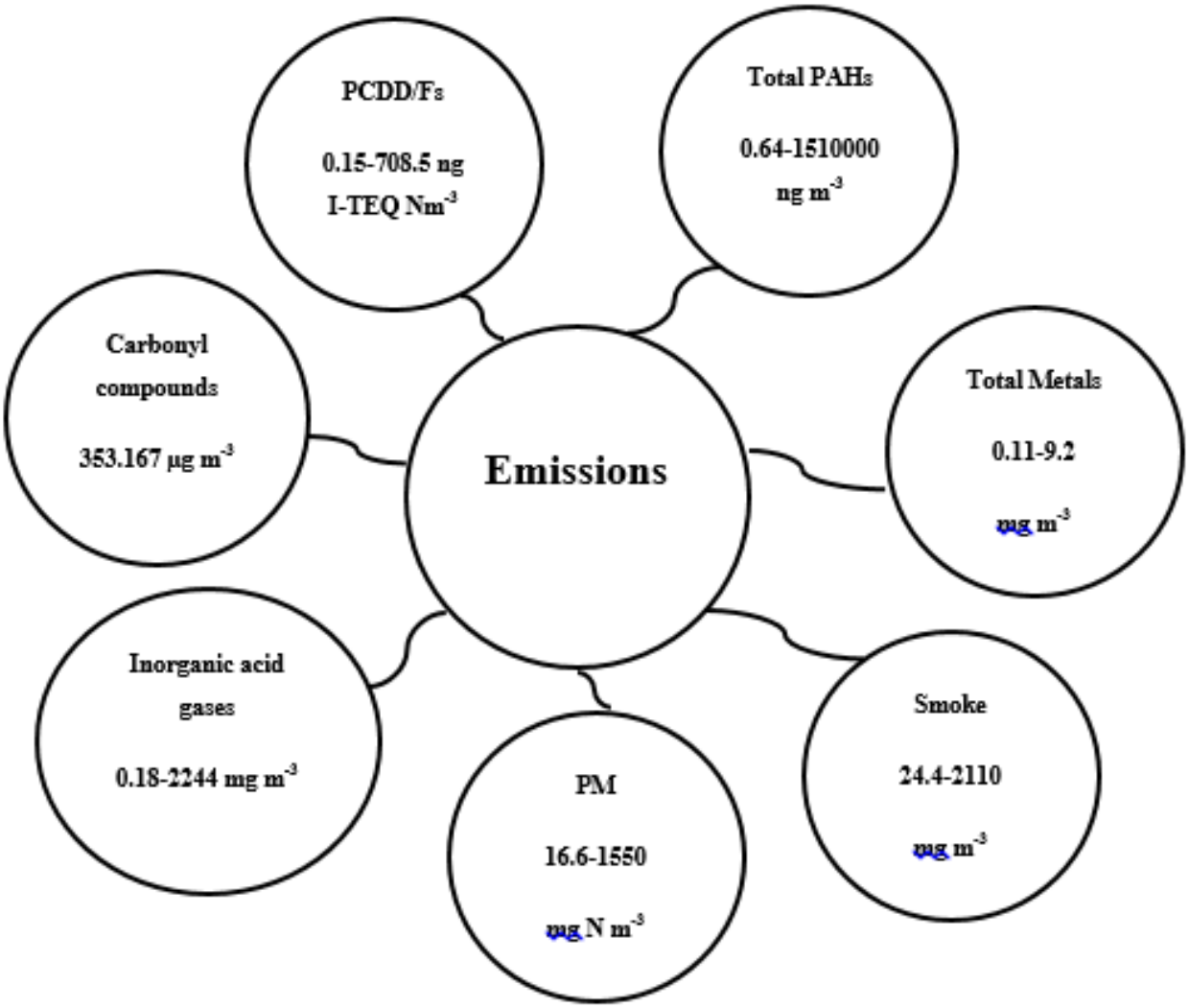


Fig. 2. Emissions from medical waste incinerators

Emissions of medical waste combustion

According to Table 2, medical wastes incineration will produce various pollutants during the burning process. These pollutants have vided range which depends on the type of incinerator, operating conditions, and APCDs. Fig. 2 shows the different emissions of MWIs.

According to the literature review, medical waste incinerators and Municipal Solid Waste Incinerators (MSWIs) are the main sources of PCDD/Fs in the atmosphere. They are also responsible for 10.7% of the emitted dioxins and furans [51, 52]. Even in MWIs, these pollutants are more significant than MSWIs

due to higher chlorine content (2%) [39]. The concentration of PCDD/PCDFs is varied and depend on combustion condition and APCDs. For instance, in a study in South Korea, the average concentration of the measured dioxin and furans at several medical waste incinerators was 9.23 ng-TEQ/Nm^3 in 2003 and 6.85 ng-TEQ/Nm^3 in 2004 that is the reason could be different APCDs [24]. Yoon et al. has measured the PCDD/PCDFs concentration in the flue gas of the incinerator stack, which was in the range of 0.151 to 101.9 ng/Sm^3 among the nineteen surveyed incinerators while four had exceeded the emission limit [3]. The same measured dioxin in research in China was beyond the recently issued standard levels in this country (0.5 ng I-TEQ/Nm^3) [39]. These concentrations have also been high (93 to 710 times) in another study [22]. The other toxic organic pollutants released from the MWIs are the PAHs, carbonyl components, acidic gases, heavy metals, and Particulate Matter (PM). Dallarosa et al. have reported the average concentration of the PAHs in the air near the medical incinerator in the range of 0.055 to 2.295 ng/m^3 [53]. Studying carbonyl components in uncontrolled combustion sources showed that the highest concentrations belong to MWI samples due to higher formaldehyde amounts in medical waste [27]. The literature shows that acidic gases and heavy metals in medical waste incinerators are more remarkable than the standard limit, except for NO_x. For instance, Zakaria et al. mentioned that NO_x and SO_2 emissions in six studied incinerators were less than the standard limit according to the Egyptian Environmental Law (Law No.4 – 1994). However, this amount is assumed very high in a study compared to the European standard [33]. The NO_x concentrations in another study were also acceptable, while the CO, SO_2, and HCl had been 11-24 times, 2-5 times, and 9-200 times higher than standard levels, respectively [10]. In another research in 2003, the average concentration of all gasses (Pb, CO, SO_2, and NO_2) in six incinerators had been in the range of Egypt Environmental Law, except for the average smoke concentration [54]. Alvim-Ferraz et al. had measured emissions, and the results show that the concentrations had been over the standard limits for the CO (11-24 times), SO_2 (2-5 times), HCl (9-200 times), Hg (1.3-266 times), and the sum of other metals (3-8 times). An additional report has observed that the cadmium is remarkably more than the predefined limit. Only the concentration of the NO_x was acceptable in this report [22]. Xie et al. investigated heavy metals in the flue gas of medical incinerators and measured values for Hg, Cd, As, Ni, Pb, Cr, and Cu were 0.012, N.A., 0.018, 0.005, 0.046, 0.011, and 0.021 mg/m^3, respectively. The measured metals are all well below the Environmental Protection Agency (EPA) emission standards [55]. In another harmful metal from MWIs is mercury which is correlated with a rise in chlorine concentration. Graney et al. estimated that 11±1% of particulate mercury originates from MWIs [56]. However, the combustion of the medical waste– using classification in source - is accounted only for about 1% of the mercury available in the air in a study [57]. Thus, the distribution of the Hg in ambient air and human's possible exposure to this toxic metal have received considerable attention. PM released from MWIs is more related to the direction of the wind. As in the direction that the wind is moving, it has the highest concentration.

Moreover, the level of it in hot season is more than cold one. Mao et al. show that none of the average daily amounts of the PM_{10} in the study zone was more than the national standard for ambient air quality (125 µg/m^3). Also, they have shown that particle concentrations in downwind were dramatically more than the concentration in upwind. Also, the average concentration of the PM was remarkably higher in March, April, and May compared to July and August [32]. It seems that the lower PM concentration in rainy months is possibly due to washing out the particles by rain.

Table 2. Concentration of pollutants remained in medical waste incinerator ashes

Country	Facility type	Operation conditions	Studied pollutants	Method	Year	Remarks	Ref.
Egypt	Batch type incinerator	Incubation at 20 ºC and 37 °C for 24±2 h colonies, volatile substances ignition in a muffle furnace at 550 ºC for 2 h	Bacterial count, Volatile substances, Lead, Cadmium	atomic absorption spectroscopy	2005	- The total concentration of bacterial count (col/kg) of ash at 20 and 37 ˚C was 0-108571.43 and 10000-178571.42, respectively. - Volatile solids of ash were % 1.26-3.09. - Lead and cadmium of ash were 5.05-118.7 and 0.1-4.56 mg/kg, respectively. - There was not much fluctuation in the bacterial count of ash samples at 20 and 37 °C between the six incinerators. - The percentage of volatile compounds in the ash samples of the six incinerators was much higher than the recommended value. -Lead and cadmium levels in ash samples were much higher than in values of developed countries. And it was more or less compared to developing countries.	[33]
UK	State-of-the-art incinerator	Samples were heated at 105 °C for 48 h in a muffle oven	PAHs PCDDs Cd As Cr Ni	HPLC	2010	- The release of PAHs into ash was much higher than in the air. Such as, BaP in bottom ash and the flue gas was 23.2 and 1.1–3.1 mg/day, respectively.	[34]
China	Rotary kiln	Samples were collected from the bag filter	PCDD/F	US EPA method 1613	2015	- The concentrations of PCDD/F in fly ash was 4.1 ng I-TEQ/g.	[39]

Table 2. Concentration of pollutants remained in medical waste incinerator ashes

Country	Facility type	Operation conditions	Studied pollutants	Method	Year	Remarks	Ref.
Taiwan	Batch-type MWIs, including the one with a mechanical (MG-MWI) and the other with a fixed grate (FG-MWI)	injection volume 1 ml, splitless injection at 310 °C, ion sources temperature at 310 °C in oven, from 50 °C to 100 °C at 20 °C/min; 100 °C to 290 °C at 3 °C/min; held at 290 °C for 40 min	PAHs	GC/MS	2001	- The mean concentration of total PAHs for MG-MWI in bottom ash (ng/g), ESP fly ash (ng/g), and WSB effluent (mg/L) was 162, 13800, and 124, respectively. These values for FG-MWI were 3480, 47000, and 62.2, respectively.	[5]
Vietnam	Grate incinerator	Samples dried in to air and sieved to less than 1 mm; 10 g of each sample, Soxhlet extracted with 200 mL of toluene for 24 h	PCDD/PCDF	Micromass Autospec Ultima system equipped with a 7890A gas chromatograph	2018	- The concentrations of PCDDs, PCDFs, and total PCDD/Fs in bottom ash were 320, 1400, and 1725 pg/g, respectively	[58]
China	Pyrolysis Gasifier incinerator	Samples extracted in Soxhlet apparatus with toluene for 24 h. temperature program of GC/MS: from 110 °C, holding for 1 min, then to 205 °C at 30 °C/min,	PCDD/PCDF	GC/MS	2011	- The concentration of PCDD/PCDF in fly ash was 0.918 ng/ton waste.	[48]

Table 2. Concentration of pollutants remained in medical waste incinerator ashes

Country	Facility type	Operation conditions	Studied pollutants	Method	Year	Remarks	Ref.
		holding for 1 min, then to 310 °C at 3 °C/min					
Indonesia	-	temperature of incinerator: around 680 °C duration: 150 min	Cu, Cd, Cr, Zn, Pb	toxicity characteristic leaching procedure (TCLP)	2019	- The concentration of Cu, Cd, Cr, Zn, and Pb were 7.10, 0.69, 2.48, 71.20, and 2.62 mg/L.	[28]
Japan	Fixed grate incinerator	Chemical agents, i.e. chelating agent, alkaline phosphoric acid solution, and acidic phosphoric acid solution were used as stabilizer.	As, Ba, Cd, Co, Cr, Cu, Fe, Hg, Mg, Mn, Mo, Ni, Pb, Sn, Zn	Japanese Leaching Test	2009	- The principal metals in the bulk fly ash were (in mg/kg): Cu (200.17–364.24), Fe (1132.5-8908.1), Mg (1576.2–4502.3), Pb (327.65–518.26), Sn (1470.4–1679.5), and Zn (1394.2–2112.1).	[59]
China	Rotary Pyrolysis kiln	The incinerator operates at 500–600 °C and a second firebox with a fluidized bed which operates at 900–1000 °C.	Cd, Cu, Pb, Ni, Zn, Hg	US EPA test method 1311–TCLP	2010	- The concentration of Cd, Cu, Pb, Ni, Zn, and Hg in the fly ash were 32.2, 1255.1, 1175.95, 755.55, 794.22, and 18.478 mg/kg.	[60]
Vietnam	Grate incinerator	Capacity: 0.2 ton/h, Average operating time: 7200 h/yr	PCDD/Fs	Method 8290A of the US EPA	2019	- The concentration of PCDD/Fs in the bottom ash was in a range 312-2650 pg/g.	[61]

Table 2. Concentration of pollutants remained in medical waste incinerator ashes

Country	Facility type	Operation conditions	Studied pollutants	Method	Year	Remarks	Ref.
Turkey	-	According to test, granulated material (<9.5 mm) extracted with in CH3COOH and NaOH solutions, at the pH 4.93±0.05 and with a liquid/solid ratio (L/S) of 20 for 18 h.	Cd, Cr, Cu, Fe, Ni, Zn	TCLP leaching test	2017	- The bottom ash contained high concentration of Cr 29.83, Cu 38.97, and Zn 13.26 mg/L and lower concentration of Cd <0.06, Fe 5.63, and Ni <0.02 mg/L.	[62]
China	-	The extraction performed using capped polypropylene bottles loaded on a rotary tumbler at 30±2 rpm for 18±2 h	Cu, Pb, Zn, Cd and Ni	TCLP (USEPA Method 1311)	2020	- The concentration on Cu, Pb, Zn, Cd, and Ni in fly ash were 6067.2, 2219.7, 24252.5, 60.3, and 227.1 mg/L, respectively.	[29]
China	-	The resolving power of the selected ion monitoring analyzer mode, temperature, and electron energy is 10,000, 250 °C and 38 eV, respectively.	PCDD/Fs, Zn, Pb, Cu, and Cd	- isotope dilution high-resolution gas chromatography–high-resolution mass spectrometry (HRGC–HRMS) - leaching toxicity–acetic acid buffer	2018	- The total concentration of PCDD/Fs in fly ash was 81.86 ng/g. - The concentration of Zn, Pb, Cu, and Cd ions in the simulated filtrate were 210.8, 41.7, 19.8, and 3.11 mg/L, respectively.	[63]

Table 2. Concentration of pollutants remained in medical waste incinerator ashes

Country	Facility type	Operation conditions	Studied pollutants	Method	Year	Remarks	Ref.
				solution method (HJ/T300-2007)			
Romania	-	- 1g of each ash sample dissolved in a mixture of concentrated acids (9.5 mL HNO3 65% and 0.5 mL HF). - Samples mineralized in Ethos UP Milestone Microwave equipment at 220 ˚C and 1500 W.	Cr, Ni, Cu, Zn, Pb, As, Cd	TCLP	2019	- The concentration of heavy metals in fly ash were Cr with value ranging from 2692 to 3860, Ni 575-682, Cu 2950-3432, Zn 16500-28630, Pb 10218-15639, As 24.9-32.6, and Cd 81-130 mg/kg dry matter.	[64]
Malaysia	Rotary kiln system	After volatilization, condensation and coagulation process due to an extreme decrement of temperature from about 1,500 °C to about 150 °C.	As, Cd, Pb, Cr, Hg	inductively coupled plasma optical emission spectrometry (ICP-OES) of the Perkin-Elmer Optima 5300 DV	2015	- The average concentration of As, Cd, Pb, Cr, and Hg in fly ash were 4.0, 6.9, 6100, 150, and <0.1 mg/kg, respectively. - The average concentration of As, Cd, Pb, Cr, and Hg in bottom ash were <0.5, <0.5, 340, 130, and <0.1 mg/kg, respectively.	[30]
Taiwan & Beijing	Rotary kiln, Pyrolysis and Gasification	Samples dried at 378 K for 24 h and ground to <0.25 mm for use.	Cu, Pb, Zn, As, Ba, Cd, Cr	inductively coupled plasma-optical emission spectrometry	2009	- The concentration of Cu, Pb, Zn, As, Ba, Cd, and Cr in raw fly ash from rotary kiln incinerator were 13000, 11800, 37100, 81.5, 1002, 60.7, and 234 mg/kg, respectively.	[65]

Table 2. Concentration of pollutants remained in medical waste incinerator ashes

Country	Facility type	Operation conditions	Studied pollutants	Method	Year	Remarks	Ref.
				(ICP-OES, PerkinElmer)		- The concentration of Cu, Pb, Zn, As, Ba, Cd, and Cr in raw fly ash from pyrolysis and gasification incinerator were 2730, 4340, 48800, 575, 1649, 84.4, and 95.0 mg/kg, respectively.	
Greece	Rotary kiln	two identical incineration lines with a daily capacity of 15 t each, temperatures: over 900 °C	As, Cd, Hg, Ag, Mo, Ni, Zn, Sb, Ba, Ga, Ge, Co, La, Ce, Cu, Pb, Y, Nb	Inductively Coupled Plasma Mass Spectrometry (ICP-MS X Series II, Thermo Scientific)	2018	- The concentration of As, Cd, Hg, Ag, Mo, Ni, Zn, Sb, Ba, Ga, Ge, Co, La, Ce, Cu, Pb, Y, and Nb in bottom ash were 11, 3.2, 1.3, 0.8, 12.3, 124, 52.7, 4.7, 3840, 2.7, 0.8, 34, 44, 81, 1287, 18, 7.3, and 0.2 mg/kg, respectively. - The concentration of As, Cd, Hg, Ag, Mo, Ni, Zn, Sb, Ba, Ga, Co, La, Ce, Cu, Pb, and Y in fly ash were 12.7, 3.3, 1.8, 4.2, 27, 22.4, 1103, 13.6, 102, 0.8, 28, 43, 53, 138.2, 135.5, and 9.8 mg/kg, respectively.	[18]
China	-	Solid samples of the fly ash, the froths and the tailings were dissolved in aqua regia (a mixture of HNO_3 and HCl at a volume ratio of 1:3).	Pb, Zn, Cu, Cd, Cr, and dioxins	Atomic absorption spectrometer AA800	2018	- The concentration of Pb, Zn, Cu, Cd, and Cr in fly ash were 2232, 8507, 794, 146, and 124 mg/kg, respectively. - The concentration of dioxins in fly ash samples were 6.98 ng I-TEQ/g.	[66]
Ghana	-	A 5 g of bottom ash weighed into 100mL polytetrafluoroethylene Teflon beaker. Two milliliters of 65% nitric acid and 5 mL of 36% hydrochloric acid	Hg, Pb, Zn, Ag, Cr, and Cd	atomic absorption spectrophotometer Agilent 240 FS in the flame mode and cold vapor mode for Hg.	2016	- The concentration of Hg, Pb, Zn, Ag, Cr, and Cd in bottom ash were 0.88, 143.80, 16417.69, 28.38, 99.30, and 7.54 mg/kg, respectively.	[67]

Table 2. Concentration of pollutants remained in medical waste incinerator ashes

Country	Facility type	Operation conditions	Studied pollutants	Method	Year	Remarks	Ref.
		were added to each sample in a fume chamber.					
China	Rotary Kiln	After combustion, the flue gas is rapidly quenched by water to keep the temperature between 180 °C and 200 °C.	Cd, Ni, Pb, As, and Hg	GC/mass spectrometer	2011	- The concentration of Cd, Ni, Pb, As, and Hg in fly ash were 12.1, 10.1, 107, 1.33, and 63.0 mg/kg, respectively.	[68]
Taiwan	-	0.5 g samples digested with 1 mL HBF4 + 5 mL HNO_3+5 mL HClO4, heating program: 20–180 °C at 10 °C/min and held isothermally for 30 min, digestion solution diluted to 25 mL with deionized water.	Ag, Al, As, Ba, Ca, Cd, Cr, Cu, Fe, Hg, K, Mg, Mn, Na, Ni, Pb, Se, Si, Zn, PCDD/F	Inductively coupled plasma atomic emission spectrometer (Jobin Yvon JY-38 Plus ICPAES)	2012	- The concentration of Ag, Al, As, Ba, Ca, Cd, Cr, Cu, Fe, Hg, K, Mg, Mn, Na, Ni, Pb, Se, Si, and Zn in fly ash were 19.0, 123, 73.9, 10.3, 3481, 11.2, 9550, 554, 48282, 8.9, 2571, 610, 1454, 73152, 9235, 39.9, 1419, 1850, and 571 mg/kg, respectively. - The concentration of PCDD/F in raw fly ash were 58.6 ng/g (6.2 ng I-TEQ/g).	[69]
China	-	Ash was weathering for 6 months, homogenized and screened by a sieve of 20 meshes, dried at 105 °C for 24 h.	Pb, Zn, Cu, Cd, Cr	-	2017	- The concentration of Pb, Zn, Cu, Cd, and Cr in fly ash were 2232, 8507, 794, 146, and 124 mg/kg, respectively.	[70]

Table 2. Concentration of pollutants remained in medical waste incinerator ashes

Country	Facility type	Operation conditions	Studied pollutants	Method	Year	Remarks	Ref.
Jordan	-	Contact time (0.33, 0.67, 1, 2, 24, and 48 h), particle size (180–300, 300–500, 500–1000, and 1000–2100 µm), pH (2, 5, 7, 9, and 11), temperature (25, 35, 45, and 55 °C), solid-liquid ratio (3/250, 3/200, 3/150, 3/100, and 3/50 g/ml).	As, Cd, Cr, Cu, Ni, Pb, Se	ICP-MS employing kinetic energy discrimination mode (KED)	2018	- The amount of leached As, Cd, Cr, Cu, Ni, Pb, and Se in bottom ash were <0.002, <0.002, 2.1, <0.6, <0.16, <0.8, <0.01 mg/L, respectively.	[71]
Greece	rotary kiln	Temperature of the combustion chambers: 1100 - 1200 °C, oxygen access of λ = 1.68	Cr, Fe, Ni, Cu, Zn, Cd, Ba, Pb	TCLP	2011	- The concentration of Cr, Fe, Ni, Cu, Zn, Cd, Ba, and Pb in untreated fly ash leachate were 0.086, 0.860, 0.076, 1.030, 13.20, 0.017, 1.840, and 5.216 mg/L, respectively. - The concentration of Cr, Fe, Ni, Cu, Zn, Cd, Ba, and Pb in untreated bottom ash leachate were 0.128, 2.401, 0.626, 1.550, 0.119, 0.0006, 2.439, and 0.005 mg/L, respectively.	[31]
Spain	-	TCLP leachate pH and ecotoxicity, expressed as EC50, obtained from the bioluminescence bioassay	Cd, Cr, Cu, Ni, Pb, Zn	TCLP	2000	- The concentration of Cd, Cr, Cu, Ni, Pb, and Zn in leachate of bottom ash were *b.r-0.11, 0.70-2.65, b.r-0.34, 0.17-0.27, 0.10-0.25, and <0.05-0.07 mg/L, respectively. - The concentration of Cd, Cr, Cu, Ni, Pb, and Zn in leachate of fly ash were 0.08-0.16, <0.05-9.75, b.r-0.05, 0.22-0.33, 0.22-0.43, and 0.06-0.07 mg/L, respectively.	[72]

Pollutants in the bottom and fly ash of medical waste incinerator

Ashes from medical waste incinerators usually contain PAHs, PCDD/Fs, and toxic heavy metals. Chen et al. investigated the distribution of PAHs in ashes. The result showed that the content of total PAHs in fly ash was 1800 times higher than in bottom ash, and PAHs with four or more rings existed in fly ash that is more carcinogenic. PAHs are not soluble in water, so they could easily attach the solid residuals [73]. In another study, the concentration of total PAHs in dry bottom ash was in a range of 637-6557 µg/kg [74]. In Zhao et al.'s study, the total concentration of PAHs in bottom ash was in a range of 10.30-38014 mg/kg [75]. In other research, total PAHs in bottom ash were 16.43- 22.50 mg/kg and in fly ash were 4.16-198.92 mg/kg [76]. Pham et al. investigated profiles of PCDD/Fs in ash samples from multiple thermal industrial processes. The ash released from steel-making plants, aluminum-recycling facilities, and medical waste incinerators had the highest emission factors. PCDD/Fs concentrated more in fly ash than bottom ash, except steel plants [61]. In a study, PCDD/F was measured, and the concentrations exceeded the standard of the Taiwan EPA [69]. Arar et al. measured PCDD/Fs in bottom ash and found that concentrations of ΣPCDD/Fs were in the range of 206–476 pg I-TEQ/g which were lower than the limit value (10,000 pg I-TEQ/g) [77]. In another study, the total PCDD/Fs in fly ash was 15.62-25.50 ng I-TEQ/g, which are exceeded the standard levels [78]. PCDD/Fs and PCBs in fly ash were higher than those in bottom ash [79]. Nguyen et al. investigated chlorinated benzenes (CBzs) in ashes and found that the concentration of ΣCBzs in fly ash (6.98-34.4 ng/g) was significantly higher than those measured in bottom ash (1.53-5.98 ng/g) [80]. Suryawan et al. measured heavy metals (Cu, Cd, Cr, Zn, and Pb) in the bottom and fly ash, and the results showed that Zn had the highest concentration among other metals. The level of metals exceeded the limits [28]. Other studies' results approved that Zn was the highest concentration of metals due to the burning of teeth, bones, and plastic products [64, 81, 82]. Hence, other research pointed that untreated fly ash has the highest concentration of Zn and Pb and lesser amounts of Cr, Fe, Ni, Cu, Cd, and Ba [31]. Others also found a similar distribution of heavy metals in fly ash [83]. However, in Valavanidis et al. study, Pb in fly ash was at a very low level. In comparison, Pb and Zn were the abundant metals in bottom ash [84]. Zhao et al. pointed that bottom ash contains a higher level of Zn, Ti, and Cr. These metals are commonly used in medical instruments, needles, and syringes [75]. According to a study, the mean concentration of iron and zinc was highest than lead and silver in bottom ash [85]. Elemental analyses of the fly ash from the medical incinerator indicated that copper, lead, chromium, and mercury were the dominant heavy metals it contained [60]. As a result of a study, cadmium is a dangerous substance; its concentration in filtered ash exceeded 30 times higher in bottom ash [64]. Fariha et al. measured trace elements (As, Cd, Pb, Cr, and Hg) in fly and bottom ash. The results showed that amounts of metals in the fly ash were higher than their content in the bottom ash. This reason is because of their properties. Trace elements are easily volatile and thus exist more in fly ash. The concentration of metals in both ashes, except Pb in fly ash, was below the standard limit as specified by the Department of Environment, Malaysian guidelines. The high lead level in the fly ash was because of plastics in medical waste [30]. Another study approved that fly ash contains more toxic metals (As, Cd, Pb, and Zn) than bottom ash. For instance, Cd in fly ash samples was about 42-62 times higher than those in bottom ash [86]. Adama et al. assessed heavy metals (Hg, Pb, Zn, Ag, Cr, and Cd) in bottom ash and found that all metals concentrations were above USEPA allowable limits for safe disposal in a landfill site [67]. In another study, the concentration of heavy metals was below the standard [55]. Wet chemical and Electron Dispersive X-ray Spectroscopy analyses showed that the bottom ash contained heavy metals (Zn, Ti, Cr, Ni, Rb, Co, Cu, Ba, Mn, Cd, Ga, As, Pb, Bi, Sb, and Li) between 0.07 to 24.1 mg/kg [87]. Bakkali et al. assessed heavy metals in ashes and found that the ashes contained

a high level of heavy metals such as Zn, Pb, Cr, and Ni in a range of 0.5-25071 mg/kg, and Cd has the lowest concentration in a range of 0-9.5 mg/kg [88]. In research, the concentration of Hg, Cd, As, Ni, Pb, Cr, and Cu in fly ash were 80, 100, 200, 140, 540, 210, and 310 mg/kg, respectively. These metals exceeded the limit values in the toxicity characteristic test [55]. According to a study, the leached of heavy metals was less than the standard limit set by EPA [71].

Assessment of trace elements in a study revel that operator parameters of incinerator like temperature, flue gas compositions, waste incineration time, and the existence of active substances during combustion such as Cl, S, Al, and Si determine the type and concentration of heavy metals in ashes [18]. Conditions of incineration influence the vaporization and transformation of volatile metals. Some metals may release to bottom ash due to being adsorbed by incombustible materials. These metals are very leachable. Other metals may trap flue gas, condense on particles, and remove as fly ash by APCDs [88]. The partitioning of heavy metals in incineration systems depends on properties like saturated vapor pressure and boiling points. Heavy metals such as Hg, Cd, and Pb are easily volatilized and enter flue gas as fly ash because of their high saturated vapor pressure. In comparison, metals like Cr, Mn, and Cu remain in bottom ash because of high boiling points [88]. Bottom ash was highly enriched in Ni, while fly ash was enriched in Zn and Pb [89].

Consequently, the content of heavy metals in fly ash of medical waste was 3.9-12.5 times higher than that in municipal waste incineration. Furthermore, fly ash is more toxic than bottom ash. That indicates higher environmental toxicity and health risk of medical incinerator fly ash [90].

Origin of medical waste emissions

The main sources of the pollutants in medical waste incineration are plastics, chlorine content, and incomplete combustion, as shown in Fig. 3.

Generally, it has been observed that medical wastes contain large amounts of plastic syringes, bottles, and other disposable products compared to municipal solid wastes [32, 35]. Therefore, medical wastes incineration will release a massive amount of Persistent Organic Pollutants (POPs) like the PCDD/Fs, which are very toxic and persistent [35, 39]. One of the most important sources of PCDD/Fs is waste incineration [91]. PAHs mainly emerge due to the incomplete combustion of natural and human sources. Human activities are account for a significant part of the PAHs in the environment. Burning diesel oil and gas lubricant oils [53], exhaustion of motoric transportation system, smoking, industrial processes, and emission of the

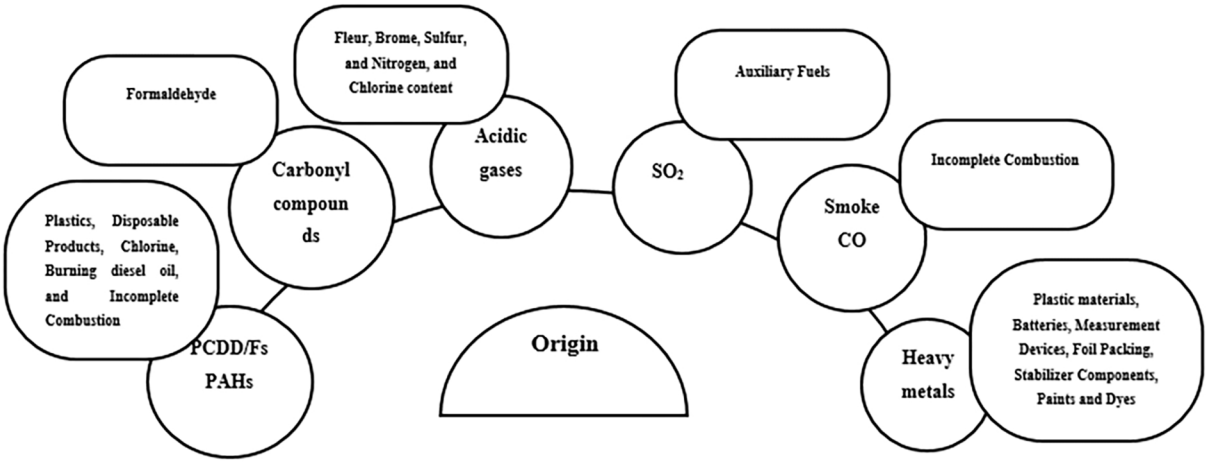


Fig. 3. Origin of medical waste incinerator emissions

flue gas of incinerators are examples of human activities [92].

Moreover, medical wastes contain 25% plastics, and PAHs are the byproduct of combusting plastics. Mao et al. have shown that the leading cause of the PAH emission in the study area (distance 1 km) was the medical incinerator, while at the reference area (distance 11 km), the vehicles were responsible [32]. The inorganic acidic gasses like chloride hydrogen, fluoride hydrogen, bromide hydrogen, NO_x, and SO_x result from combusting elements like chlorine, fleur, brome, sulfur, and nitrogen available in wastes. Chloride hydrogen in many incinerators is due to the Cl_2-contained wastes, especially plastic wastes like PVC [92]. The SO_2 emissions are produced from the sulfur available in medical wastes and auxiliary fuels, while the smoke and CO are the direct reason for the incomplete combustion of organic components. It has been proven that inorganic materials are not destroyed during combustion and appear in incinerators in bottom ash and particulate matter in the stack. There are noxious metals in medical waste, which have the sources such as surgery blades, batteries, measurement devices, foil packing, and plastics. For instance, the PVC-made objects encompass lead-contained stabilizer components, and lead also is found in paints and dyes [33]. The same discussion can be done for mercury. The medical wastes related to thermometers, mercury batteries, amalgam from dental fillings, and other residues mercury manipulation are the known sources for it [36]. Hence, sharp objects, radioisotope shields, chemotherapy waste, laboratory chemicals, and pigments contain a large amount of Pb, Zn, Cd, and Fe [28]. Emissions of arsenic and Ag are related to medicines and radiographic plates, while Ni, Cr, Co, and Mo are because of medical equipment and tools produced from stainless steel [18]. Medical waste incinerators are a mixture of heavy metals.

Effective factors on the level of emissions

Various factors could affect the emissions level, such as waste composition, waste type, segregation practice, incinerator type, combustion condition (like designed temperature, retention time, excess oxygen level), and APCDs. Table 3 has classified these factors for each pollutant.

Studying the PCDD/PCDFs emission profile shows that these pollutants had a rising trend from 2000 to 2005 due to the increase in beds, population, hospitals, clinics and medical labs, and medical wastes [93]. So, with increasing waste volume, dioxin and furan emissions increase. The main reason for high concentrations of PCDD/PCDFs is the lower temperature (250-450 °C) during the start-up and shouting down periods in incinerators [11, 13]. The emissions level is different for each type of incinerator. Higher levels of PAHs have been observed in MG-MWI rather than FG-MWI. As mentioned before, higher content of plastic in feeding waste would cause higher PAHs. Researchers found that the special medical wastes that the FGMWI incinerated contained much lower plastic content than the general medical waste incinerated by the MG-MWI. Also, the feeding rate for the former was lower than the latter [5, 23]. Despite all these studies, Yoon et al. contradict the relation between PCDDs/PCDFs emissions influencing factors such as incinerator/operation type, capacity, APCDs, start-up date [3].

Experience of the operator in incineration plant is important. Bujak et al. observed that a large amount of SO_2 emission took place precisely during the waste loading stage in a specified working shift, which shows the importance of the experience level of the workers [49]. With any rise in CO concentration in incomplete combustion, PAHs will increase due to their direct relation [94]. Some factors increase smoke level during the plastic containers incineration like (a) the cardboard containers are made of cellulose fibers while the plastic ones are made of petroleum, (b) the plastic structure is more rigid than the cardboard structure and need more energy to be burnt, (c) comparatively, more air-exposed surfaces and good air circulation in cardboard containers, and also the plastics components tendency to stick to each other during incineration slower the combustion process and led to higher smoke emissions [15].

Table 3. Effective factors on concentration of emissions from medical waste incinerator

Pollutant	Affected factors	Remarks	Ref.
PCDD/Fs	○ Waste composition (amount of chlorine) ○ Waste type ○ Waste classification ○ Management methodology ○ Incinerator type ○ Furnace design ○ Combustion condition (like designed temperature, retention time, and excess oxygen amount) ○ Feeding and depleting methods ○ During of operation ○ APCDS	- In the absence of PVC, such components could not be produced. - Poor performance of APCDs, high chlorine levels, discontinuous operations, and irregular waste feeding produce large amounts of PCDD/F and vice versa. - Small incinerators emit higher dioxin levels than large incinerators due to may have a weekly function of combustion chambers, inappropriate APCDs, irregular feedings, open gates during waste feeds, and discontinuous waste combustion. - Dioxin emission increases significantly during the shout down and start-up of the incinerator.	[11, 35, 38, 40, 44, 47, 50, 92, 94, 95]
PAHs	○ Incinerator types ○ Feedstock compositions ○ Feedstock rate ○ Auxiliary fuel ○ Combustion condition (like the combustion temperature, retention time, and excessive air) ○ APCDS ○ Excess air coefficient ○ Additives	- During the incinerator's start-up, the PAH emission rises. - Using suitable APCDs significantly reduces carcinogenic potential relevant to the PAH emissions in residential regions. - Regarding the incinerator types, observations approve that the total concentration of the PAHs for the mechanical grate MWIs is more than that in the fixed grate MWIs.	[5, 23, 73, 92]

Table 3. Effective factors on concentration of emissions from medical waste incinerator

Pollutant	Affected factors	Remarks	Ref.
Carbonyl component	○ Technical condition ○ Combustion site (like the open or closed chamber)	- The highest concentrations occurred in open space combustion sites.	[27]
SO_2	○ Medical wastes incinerated ○ Effective controlling system ○ Auxiliary fuel ○ APCDS ○ Experience level of workers	- An incinerator that contained a massive amount of organic components used kidney-washing filters, ineffective control systems, and Kerosene fuel had a higher amount of SO_2 emissions.	[33]
CO	○ Retention time ○ Temperature ○ Mixing ○ Combustion function ○ APCDS ○ Chlorine	- Short retention time, low temperature, and weaker mixing release low CO levels. - High CO concentration occurs in incomplete combustion in which incomplete mixing or transient states in inadequate oxygen provision. - A very modern incinerator with two chambers, a good scrubber controlling system, proper operation, and an experienced operator had the minimum CO concentration.	[33, 39, 94, 96]
Smoke	○ Combustion condition (retention time, temperature, mixed of air and fuel)	- An ideal combustion condition like adequate retention time, suitable temperature, well-mixed air, and fuel leads to smoke reduction. - The average amount of smoke in plastic container incineration is about 2.61 times greater than that in cardboard ones.	[15, 33]
Heavy metals	○ Combustion temperature ○ pH	- Heavy metals could be controlled for different types of metals, at different combustion temperatures. - In the neutral pH, the concentration of most heavy metals in the ash were minimum. Whereas in acidic or alkaline pH, leaching toxicity enhanced.	[60, 97]

Emissions effect on health and environment

The persistent organic pollutants (POPs), like dioxins and furans, are very robust during the degradation process in the environment. They can travel farther from their origins using the air and water, accumulate in water and soil ecosystems, and have severe acute and chronic effects on human, animal, and herbal organisms [21, 98]. EPA has identified medical wastes as the third major source of dioxin emissions in the air as one of the most toxic components to humans [99]. The dioxin side-effects are Immune system malfunction, sexual disorders, congenital disorders, liver defects, weight loss, endocrine disruption, neurotoxicity, organ toxicity, and numerous transient acute health effects [61, 100]. Dioxin is classified as one of the carcinogen components for humans known by the International Agency for Research on Cancer (IARC) [99]. Fig. 4 shows cancer statistics among the unexposed and exposed people to pollutants in the vicinity of a waste incineration plant between 2005 and 2014 [101].

Fig. 4 shows that the incidence of cancer is higher among men than women. Lung cancer is the most common type of cancer. Between 2005 and 2009, acute myeloid leukemia, myelodysplastic syndromes, and myeloma were observed in exposed women, and soft tissue sarcomas, myeloma, and lung cancer were observed in exposed men. Between 2010 and 2014, there was no high prevalence in women, while men had higher myeloma and lung cancer rates. Distance from incinerators, their count, and the other combustion sources producing these pollutants are factors that impact the rate of vulnerability from such pollutants [32].

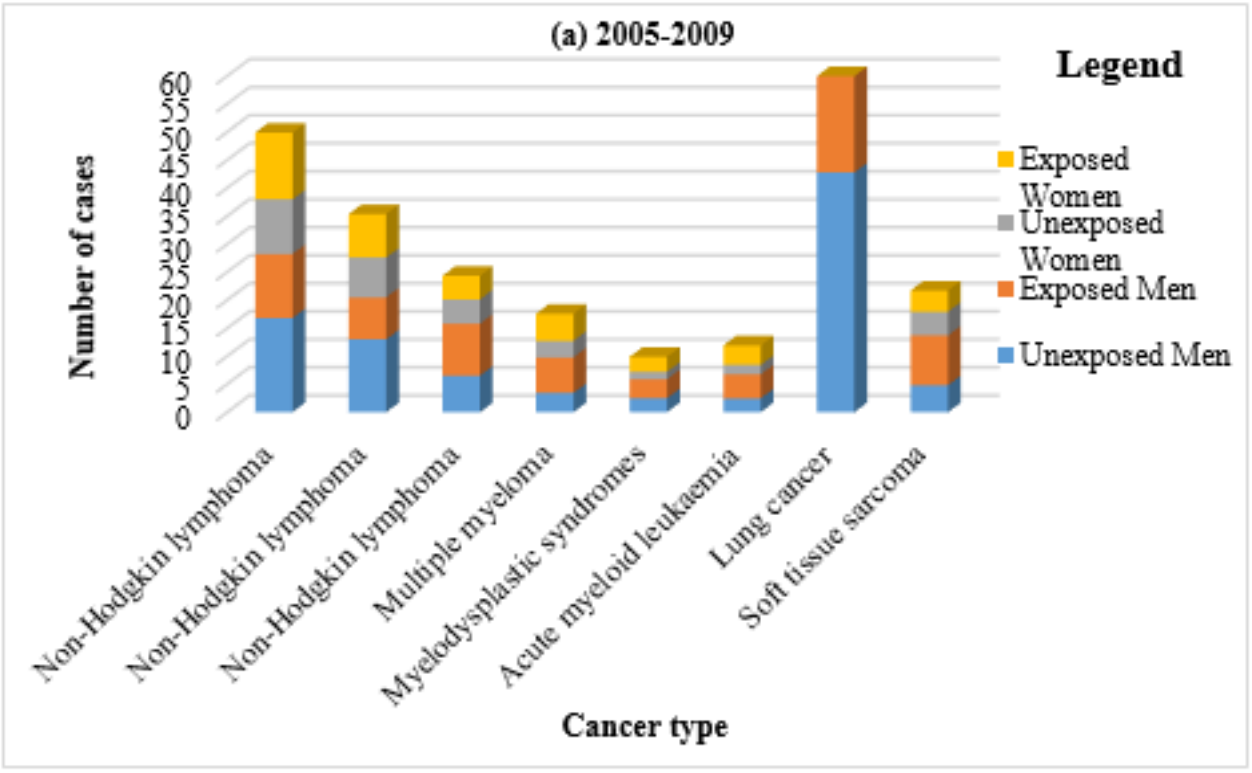
On the other hand, the PAHs are pollutants available everywhere and have been proved most of them to be very mutagen and carcinogen [92]. Therefore, some PAHs are categorized as probable human carcinogens, and their emissions to the air in residential areas should be concerned [32]. Besides, heavy metals have an adverse effect on human beings. For instance, mercury is a very well-known neurotoxin that can pass through blood-brain barriers and the placenta. Suppose that the Hg-contained components enter the incinerator or other waste-refining technologies in combination with infectious wastes. In that case, the Hg will pollute the environment, and then the air polluted with it enters a worldwide distribution cycle poisoning the fishes and the wildlife [99]. Hence, these pollutants enter the human body via the respiratory system, digestive system, and skin [27] and trace harmful effects like respiratory diseases, cancer, congenital disorders in the body, animals, plants, buildings, and destruction of visibility [33].

Standard limits of emissions in air and ashes

Emissions of incinerators could not be eliminated. So, the standard level has been set to save human beings and the environment from adverse effects. Table 4 presents the regulated standards of the medical waste incinerator emissions.

The concentration of PCDD/Fs, acidic gases except for NO_x, and PM in the air frequently exceeded the standard levels. However, the amount of PAHs rarely exceeded the limits because of the minimum PAHs produced by MWIs. The concentration of heavy metals usually exceeded the standards. Consequently, for reducing the emissions of MWIs, it should provide the appropriate APCDs and well operation conditions.

The levels of PCDD/Fs and heavy metals in ashes exceeded the standard limit. However, heavy metals leached almost always are lower than limits.



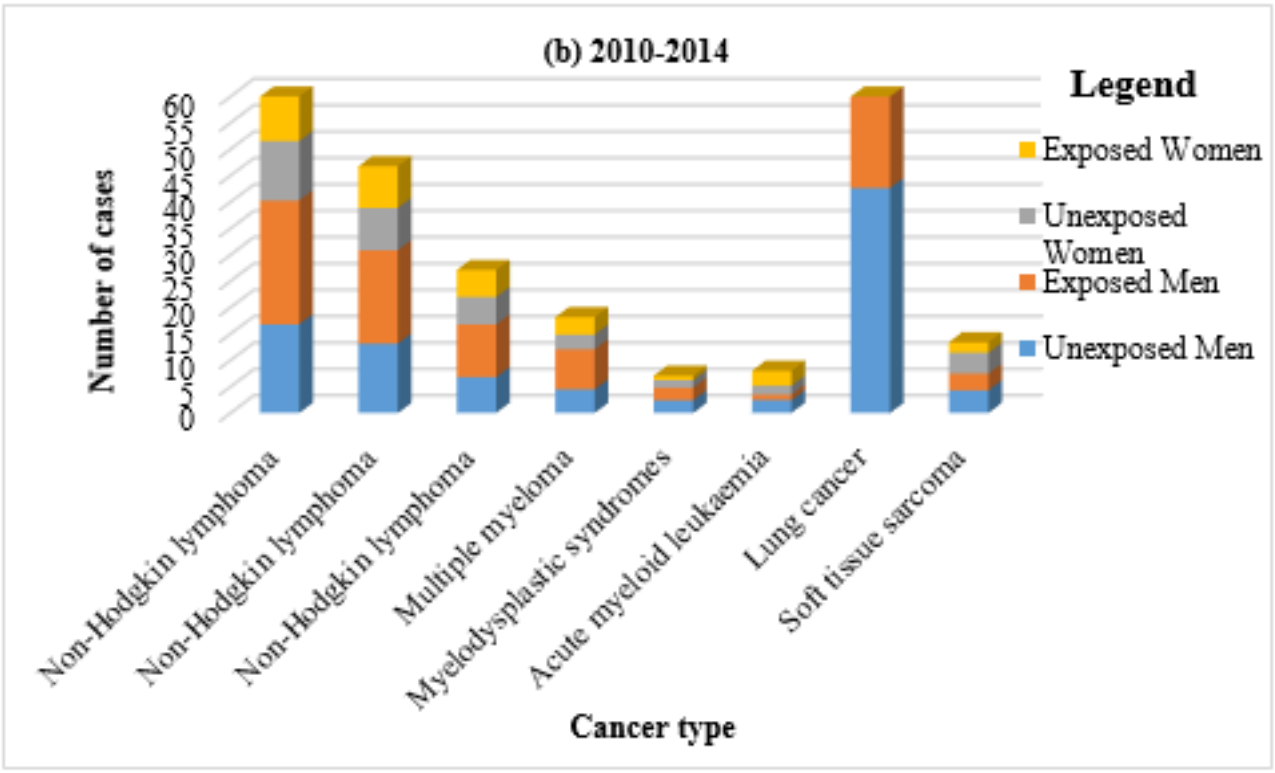


Fig. 4. Cancers among unexposed and exposed people in the vicinity of a waste incineration plant

Table 4. Medical waste incinerator emissions standard

Pollutant	Law	Exposure/ Capacity (ton/h)	Level	Remarks	Ref.
PCDD/Fs	Portuguese and European legislations	6-8 h average	0.1 ng/m^3 (ITEQ units)	-	[22]
	Emission standards in South Korea	4>	0.1 ng-TEQ/Sm^3	-	[3]
	(After 2004.07.20)	1-4	1 ng-TEQ/Sm^3		
		0.2-1	5 ng-TEQ/Sm^3		
		0.025-0.2	5 ng-TEQ/Sm^3		
	Emission standard in China	-	0.5 ng I-TEQ/Nm^3	-	[39]
	National standard in China	-	1 ng TEQ/Nm^3	-	[102]
	Health care institutions in Colombia	600 kg/month	2 ng I-TEQ/Nm^3	-	[50]
	Emission standard in China	-	3.0 ng I-TEQ/g	Fly ash limit	[39]
	-	-	1.0 ng-TEQ/g	Fly ash limit	[35]
	US EPA 1997b	-	2.3 ng TEQ/[1]dscm	-	[92]
	EPA – [2]MACT	-	0.40 ng TEQ/dscm	-	[92]
	HWC 2004	-	0.20 ng TEQ/dscm	-	[92]
	Taiwan EPA, 2008	-	1 ng I-TEQ/g	Fly ash	[69]
PAHs	European Union standard	-	1 ng/m^3	There is no allowable limit for the incinerator stack, and this value is for ambient air.	[46]
	WHO guideline	-	1 ng/m^3	There is no allowable limit for the incinerator stack,	[46]

dry standard cubic meter
maximum achievable control technology

Table 4. Medical waste incinerator emissions standard

Pollutant	Law	Exposure/ Capacity (ton/h)	Level	Remarks	Ref.
				and this value is for ambient air.	
	EPA – MACT	-	99.99 %	Destruction removal efficiency standard	[92]
	HWC 2004	-	99.99 %	Destruction removal efficiency standard	[92]
PCBs	EPA – MACT	-	99.9999 %	Destruction removal efficiency standard	[92]
	HWC 2004	-	99.9990 %	Destruction removal efficiency standard	[92]
SO_2	Portuguese and European legislations	Daily averages	50 mg/m^3	-	[22]
	European Union limit	Maximum allowed	50 mg/m^3	-	[13]
	Egyptian environmental law (law No-4 -1994)	Maximum allowed	4000 mg/m^3	-	[33]
	European limit	Maximum allowed	300 mg/m^3	-	[33]
	Average daily permissible	Daily averages	50 mg/Nm^3	Emission standard into the atmosphere	[49]
	US EPA 1997	-	55 [3]ppmv	-	[92]
NO_x	Portuguese and European legislation	Daily averages	400 mg/m^3	-	[22]
	Egyptian environmental law (law No-4 -1994)	-	300 mg/m^3	-	[33]
	European limit	-	100 mg/m^3	-	[33]
	European Commission daily maximum standard	Daily maximum	400 mg/m^3	-	[13]

[3] parts per million by volume

Table 4. Medical waste incinerator emissions standard

Pollutant	Law	Exposure/ Capacity (ton/h)	Level	Remarks	Ref.
	Average daily permissible	Daily averages	200 mg/Nm^3	Emission standard into the atmosphere	[49]
	MEF 1998	-	450 mg/Nm^3	-	[92]
	US EPA 1997	-	250 ppmv	-	[92]
HCl	Portuguese and European legislation	Daily averages	10 mg/m^3	-	[22]
	Average daily permissible	Daily averages	10 mg/Nm^3	Emission standard into the atmosphere	[49]
	MEF 1998	-	50 mg/Nm^3	-	[92]
	US EPA 1997	-	100 ppmv	-	[92]
	EPA – MACT	-	1.5 ppmv	-	[92]
	HWC 2004	-	0.18 ppmv	-	[92]
VOCs	MEF 1998	-	≤0.01%	In ash	[92]
HF	Average daily permissible	Daily averages	1 mg/Nm^3	Emission standard into the atmosphere	[49]
CO	Egyptian environmental law (law No-4 -1994)	Maximum allowed	4000 mg/m^3	This number is set for fuel combustion sources, and no limit is set for medical waste incinerators.	[33]
	European legislations	Maximum allowed	100 mg/m^3	-	[33]
	Portuguese and European legislation	Daily averages	50 mg/m^3	-	[22]
	Average daily permissible	Daily averages	50 mg/Nm^3	Emission standard into the atmosphere	[49]
	US EPA 1997	-	40 ppmv	-	[92]
	EPA – MACT	-	100 ppmv	-	[92]
	HWC 2004	-	100 ppmv	-	[92]

Table 4. Medical waste incinerator emissions standard

Pollutant	Law	Exposure/ Capacity (ton/h)	Level	Remarks	Ref.
Smoke	Foreign limits	-	30 to 180 mg/m³	-	[33]
	Egyptian environmental law (law No-4 -1994)		250 mg/m³	Limit of smoke in the emissions of sources of fuel combustion	[33]
PM	Portuguese and European legislations	Daily averages	10 mg/m^3	-	[22]
		30 min averages	30 mg/m^3		
	Average daily permissible	Daily averages	10 mg/Nm^3	Emission standard into the atmosphere	[49]
	Health care institutions in Colombia	600 kg/month	80 mg/Nm^3	-	[50]
	MEF 1998	-	150 mg/Nm^3	-	[92]
	US EPA 1997	-	34 mg/dscm	-	[92]
	EPA – MACT	-	34 mg/dscm	-	[92]
	HWC 2004	-	1.6 mg/dscm	-	[92]
PM_{10}	National ambient air quality standard of Taiwan	Daily averages	125 µg/m^3	-	[32]
TOC	Average daily permissible	Daily averages	10 mg/Nm^3	Emission standard into the atmosphere	[49]
Ag	USEPA allowable limits for waste disposal to landfill	-	5.0 mg/kg	Bottom ash	[67]
Se	EPA	-	1.0 mg/L	Leached in ash	[71]
Hg	Portuguese and European legislations	30 min to 8 h averages	0.05 mg/m^3	-	[22]
	MEF 1998	-	0.05 mg/Nm^3	-	[92]
	US EPA 1997	-	550 µg/dscm	-	[92]

Table 4. Medical waste incinerator emissions standard

Pollutant	Law	Exposure/ Capacity (ton/h)	Level	Remarks	Ref.
	EPA – MACT	-	130 µg/dscm	-	[92]
	HWC 2004	-	8 µg/dscm	-	[92]
	Department of Environment, Malaysian guidelines for the Application limits of special management of schedule waste	-	20 mg/kg	In ashes	[30]
	USEPA allowable limits for waste disposal to landfill	-	0.2 mg/kg	Bottom ash	[67]
	EPA	-	0.2 mg/L	Leached in ash	[103]
Cd + Tl	Portuguese and European legislations	30 min to 8 h averages	0.05 mg/m^3	-	[22]
Cd	MEF 1998	-	0.05 mg/Nm^3	-	[92]
	US EPA 1997	-	160 µg/dscm	-	[92]
	EPA – MACT	-	59 µg/dscm	-	[92]
	HWC 2004	-	6.5 µg/dscm	-	[92]
	Department of Environment, Malaysian guidelines for the application limits of special management of schedule waste	-	100 mg/kg	In ashes	[30]
	USEPA allowable limits for waste disposal to landfill	-	1.0 mg/kg	Bottom ash	[67]
	EPA	-	1.0 mg/L	Leached in ash	[71]

Table 4. Medical waste incinerator emissions standard

Pollutant	Law	Exposure/ Capacity (ton/h)	Level	Remarks	Ref.
The sum of concentrations of the other metals	Portuguese and European legislation	30 min to 8 h averages	0.5 mg/m^3	-	[22]
Pb	Egyptian environmental law (law No-4 -1994)	-	20 mg/m^3	This amount is for lead emitted from industrial sources, and there is no limit for lead emitted from incinerators.	[33]
	MEF 1998	-	0.5 mg/Nm^3	-	[92]
	US EPA 1997	-	1200 µg/dscm	-	[92]
	EPA – MACT	-	59 µg/dscm	-	[92]
	HWC 2004	-	6.5 µg/dscm	-	[92]
	Department of Environment, Malaysian guidelines for the application limits of special management of schedule waste	-	1000 mg/kg	In ashes	[30]
	USEPA allowable limits for waste disposal to landfill	-	5.0 mg/kg	Bottom ash	[67]
	USEPA allowable limits for waste disposal to landfill	-	5.0 mg/kg	Bottom ash	[67]
	EPA	-	5.0 mg/L	Leached in ash	[103]
Pb+Cr+Cu+Mn	Foreign limits	-	5 mg/m^3	-	[33]
Cu	EPA	-	100.0 mg/L	Leached in ash	[71]

Table 4. Medical waste incinerator emissions standard

Pollutant	Law	Exposure/ Capacity (ton/h)	Level	Remarks	Ref.
Cr	MEF 1998	-	0.5 mg/Nm^3	-	[92]
	EPA – MACT	-	84 µg/dscm	-	[92]
	HWC 2004	-	8.9 µg/dscm	-	[92]
	Department of Environment, Malaysian guidelines for the application limits of special management of schedule waste	-	2500 mg/kg	In ashes	[30]
	USEPA allowable limits for waste disposal to landfill	-	5.0 mg/kg	Bottom ash	[67]
	EPA	-	5.0 mg/L	Leached in ash	[71]
As	MEF 1998	-	0.5 mg/Nm^3	-	[92]
	EPA – MACT	-	84 µg/dscm	-	[92]
	HWC 2004	-	8.9 µg/dscm	-	[92]
	Department of Environment, malaysian guidelines for the application limits of special management of schedule waste	-	500 mg/kg	In ashes	[30]
	EPA	-	5.0 mg/L	Leached in ash	[71]
Be	EPA – MACT	-	84 µg/dscm	-	[92]
	HWC 2004	-	8.9 µg/dscm	-	[92]
Ba	EPA	-	100.0 mg/L	Leached in ash	[103]
Ni	EPA	-	100.0 mg/L	Leached in ash	[71]

Control systems of pollutants

One big problem in the waste incineration process is pollutants emission out of the stack required to be kept in standard ranges. There are some air pollution control devices (APCDs) to fulfill this obligation like the gravity settlers, mechanical cyclones, fabric filters, and electrostatic precipitators for the particulate matters, and the wet scrubber, dry scrubber, and solid sorbent beds for the gasses and evaporations [33, 104]. The most proper APCD is selected considering the type and concentration of the pollutants [36]. Other researchers also attest that operating suitable maintenance is not enough to work with medical waste incinerators, and controlling the atmospheric pollutions is essential [4, 10, 22, 25, 42, 50]. The emission amounts of some pollutants like the PAHs and PCDDs are 1-2 times less than the same reported values in 1980s studies, generally due to the better combustion conditions and appropriate APCDs [34]. According to a study, the emitted dioxin from the medical waste incinerators has been seen in the form of gaseous pollutants [105]. It could be mentioned that PAHs with lower molecular weight (MW) were found in the gaseous phase, while Higher MW of PAHs had a significant fraction in the particle phase [73]. Hence, using devices for removing gases is recommended in dealing with such pollutants. For instance, Lee et al. showed that the total PAHs removal efficiency using the ESP and WSB for MG-MWI was equal to 0.276% and 14.9%, respectively, while the same values for FG-MWI were 2.08% and 13.8%, respectively [5]. The APCDs use should be based on the properties of pollutants that are going removed. For instance, in a study, the used APCDs had not been practicable enough for PAHs because they were more appropriate to remove particulate pollutants while the PAH compounds mainly existed in the gas phase. In comparison, removal efficiency for WSB was higher than ESP for both of the incinerators. Conclusively, the WSP had been more efficient in reducing PAHs [23]. Other research approved that ESP and WSB were efficient methods for controlling PAHs emitted from medical waste incinerators to ambient air [73]. In another study, the efficiencies of WSB were higher for dioxins, Hg, and SO_2, while for other pollutants, the fabric filter/dry scrubber was more efficient [36]. Using the ESP and WSB together as APCDs shows a reduction in total PAHs and benzo-[a]pyrene equivalent (total BaPeq) emission concentrations in both incinerators from 2220 to 1870 and 50 to 12.4 ug/m^3, respectively. The removal efficiency for total BaPeq was higher than PAHs because the former compounds were mainly presented in the particulate phase, and the latter compounds were mainly presented in the gas phase [23]. Chen et al. reported that the total PCBs emission efficiency using bag filters under the two different conditions were 69% and 85% [26]. Additional research approved that the dioxins can be reduced using the semi-dry scrubber and activated carbon and absorbed in bag filters [48].

Consequently, without controlling the atmospheric pollutants, medical waste incineration will not obey the legal emission limits even by applying correct operation and maintenance methods [10, 25].

Management methods of medical waste incineration

Medical wastes, hazardous wastes, and municipal solid wastes incineration as the known primary sources of dioxin and furan emissions should attract more attention, knowing that the rate of incinerated waste has been predicted to increase in the future [102]. By increasing waste, was should attempt to find methods for reducing emissions. The best way for PAHs emission reduction is reducing the plastic products in medical wastes. It has also been observed that the PAHs and soot are produced while polystyrene (PS), polyethylene,

and benzene are synthesizing. A study reveals that while an incinerator was heated at 1000 °C, the PAHs forming PS ratio was reduced, and even more heating resulted in more reduction [32]. Also, another study pointed that if the post-combustion temperature during the start-up or shout down reaches 850 °C, or even more, a reduction could be observed in PCDD/PCDF level [38]. So, the temperature should not be let to fall lower than optimum values. Another way of controlling emissions is separating solid waste at the source. According to Alvim-Ferraz et al.'s research, applying exact management and rigorous separation practices causes an 80% reduction in waste incinerated. This reduction of mass causes Hg and Pb emissions to be omitted and decreases PM, As, Cd, Cr, Mn, and Ni concentrations by 98%, 90%, 92%, 84%, 77%, and 92%, respectively [10]. Others conducted a similar study and were omitted particulate matters, dioxins, As, Cd, Cr, Mn, and Ni by 98%, 99.5%, 90%, 92%, 84%, 77%, and 92%, respectively. The corresponding values for the SO_2 and NO_x were 93%, and CO and HCl were more than 99%. Lead and mercury were as well omitted totally [22]. Another way is the use of colored plastic should be banned because it causes a high level of Pb, Cr, and Cd in the ash of medical waste [106]. Even more, the degree of segregation is effective. Comparing the different segregation scenarios (USUSeg and RIGSeg) shows that for RIGSeg quantity of waste in Group IV (specific Healthcare wastes with compulsory incineration) is decreased, and the amount of the waste incinerated. So, it is crucial to implement segregation practice as perfectly as possible to get to the minimum emissions. Another way to have lower organic emissions is equipped incinerators with at least two combustion chambers and more than 1000 °C temperatures at all stages. The flue gas temperature must be fallen as soon as possible from 450 to less than 200 °C in a cooling tower, and the excess oxygen (V/V) should be kept at 6 to 10%. Also, a shorter retention time for the particulates in the optimal temperature range (350–450 °C) is recommended [11, 40]. In many countries, the lack of devices for measuring the oxygen flow is a deficiency that the workers are dealing with [11]. Therefore, as an efficient way, incinerators should be equipped with oxygen meter devices. Some mismanagement results in inadequate waste treatment like; feeding during the start-up while the incinerator and its entries are not warm, feeding each batch while the complete utilizing temperature has not been attained, and not controlling the temperature at the first chamber, which results in temperature fall due to feeding more humid wastes [50]. Therefore, high temperature, high retention time, well-mixing, controlling the waste feeding rate, and combustion air must be kept during the incineration process [4, 25].

Further replacing the conventional incinerators with newer ones could help to reduce emissions. They have some advantages like; lower pollution risk, lower utilization costs, and easy preserving high temperature [12, 36]. It is essential to limit the feeding rate to slightly less than 0.2 ton/d for controlling emissions concentrations [15]. After incineration, the fly and bottom ash should be treated properly before being landfilled [39].

Conclusion

Incineration has been used widely for medical waste disposal due to its advantages like reducing the mass and volume of waste, destroying of toxic organic components, and possibly for recycling energy during combustion. On the other hand, medical waste incinerators are the major sources of PAHs, PCDD/Fs, toxic acidic gases, and heavy metals in the environment. Their concentrations depend on waste type, APCDs, incinerator type, operation parameters, waste compositions, and segregation practice. These pollutants are being evaporated into the air or stick to the surface of some fine solid particulate. Humans are being exposed to these components via respiration, food, or

skin contact. Reducing medical waste at the source and recycling the medical PVC plastics to reduce emissions in the waste combustion process is recommended.

On the other hand, many incinerators that are being used are old-fashioned and are operated by less-aware, less-educated operators, who work extraordinarily long hours that will finally lead to a higher amount of emissions. Forbidding the use of these old MWIs or upgrading them to prevent out-of-standard PCDD/Fs emissions should be included in the plan. Moreover, using high-efficiency pollution control systems in medical incinerators to protect public health is vital. It is a feasible recommendation that less frequent start-ups and shout-downs in utilizing incinerators – at most once a week – will positively affect the emission rate due to avoiding the incomplete combustion durations. All in all, finding effective methods in medical plastic wastes treatment needs further study.

Financial supports

Research Center for Environmental Health Technology, Iran University of Medical Sciences, Tehran, Iran (Grant Number 99-1-61-18653).

Competing interests

The authors of this article declare that they have no conflict of interests.

Acknowledgements

The authors gratefully acknowledge the financial support of the Research Center for Environmental Health Technology, Iran University of Medical Sciences, Tehran, Iran (Grant Number 99-1-61-18653).

Ethical considerations

Ethical issues (Including plagiarism, Informed Consent, misconduct, data fabrication and/or falsification, double publication and/or submission, redundancy, etc) have been completely observed by the authors.

References

1. Sayan İ. Servqual model in evaluation of healthcare service quality; application of a research and training hospital. Turan: Stratejik Arastirmalar Merkezi. 2021;13(49):286-99.

2. Liu HC, Wu J, Li P. Assessment of health-care waste disposal methods using a VIKOR-based fuzzy multi-criteria decision making method. Waste Management. 2013;33(12):2744-51.

3. Yoon YW, Jeon TW, Son JI, Kim KY, Kwon EH, Shin SK, et al. Characteristics of PCDDs/PCDFs in stack gas from medical waste incinerators. Chemosphere. 2017;188:478-485.

4. Ferraz MA, Afonso SA. Dioxin emission factors for the incineration of different medical waste types. Arch Environ Contam Toxicol. 2003;44(4):460-6.

5. Lee WJ, Liow MC, Tsai PJ, Hsieh LT. Emission of polycyclic aromatic hydrocarbons from medical waste incinerators. Atmospheric Environment. 2002;36(5):781-90.

6. Shinee E, Gombojav E, Nishimura A, Hamajima N, Ito K. Healthcare waste management in the capital city of Mongolia. Waste management (Elmsford). 2008;28(2):435-41.

7. Rajan R, Robin DT, Vandanarani M. Biomedical waste management in Ayurveda hospitals–current practices and future prospectives. Journal of Ayurveda and integrative medicine. 2019 Jul 1;10(3):214-21.

8. Fang S, Jiang L, Li P, Bai J, Chang C. Study on pyrolysis products characteristics of medical waste and fractional condensation of the pyrolysis oil. Energy. 2020;195:116969.

9. Diaz LF, Savage GM, Eggerth LL. Alternatives for the treatment and disposal

of healthcare wastes in developing countries. Waste Management. 2005;25(6 SPEC. ISS.):626-37.

10. Alvim-Ferraz MC, Afonso SA. Incineration of different types of medical wastes: Emission factors for particulate matter and heavy metals. Environtal Science & Technology. 2003;37(14):3152-7.

11. El-Hamouz AM. Medical waste incineration in Nablus City, West Bank: A case study. Arabian Journal for Science and Engineering. 2002 Apr 1;27(1):29-40.

12. Jangsawang W, Fungtammasan B, Kerdsuwan S. Effects of operating parameters on the combustion of medical waste in a controlled air incinerator. Energy Conversion and Management. 2005 Dec 1;46(20):3137-49.

13. Njagi NA, Oloo MA, Kithinji J, Kithinji MJ. Health-care waste incineration and related dangers to public health: Case study of the two teaching and referral hospitals in Kenya. Journal of community health. 2012 Dec;37(6):1168-71.

14. Trinh VT, Van HT, Pham QH, Trinh MV, Bui HM. Treatment of medical solid waste using an Air Flow controlled incinerator. Polish Journal of Chemical Technology. 2020;22(1).

15. Raila EM, Anderson DO. Black carbon emission reduction strategies in healthcare industry for effective global climate change management. Waste Management & Research. 2017;35(4):416-25.

16. Zhao W, Van Der Voet E, Huppes G, Zhang Y. Comparative life cycle assessments of incineration and non-incineration treatments for medical waste. The International journal of life cycle assessment. 2009 Mar;14(2):114-21.

17. Kerchich Y, Moussaoui Y, Scholl G, Eppe G. Determination of PCDD/Fs and dl-PCBs in ash and particle samples generated by an incineration plant for hospital and industrial waste in Northern of Algeria. Atmospheric Pollution Research Journal. 2018(9):968-75.

18. Tsakalou C, Papamarkou S, Tsakiridis PE, Bartzas G, Tsakalakis K. Characterization and leachability evaluation of medical wastes incineration fly and bottom ashes and their vitrification outgrowths. Journal of environmental chemical engineering. 2018 Feb 1;6(1):367-76.

19. Gidarakos E, Petrantonaki M, Anastasiadou K, Schramm KW. Characterization and hazard evaluation of bottom ash produced from incinerated hospital waste. Journal of hazardous materials. 2009 Dec 30;172(2-3):935-42.

20. Rahim FL, Hassim MH, Mokhtar MM, Kidam K. Health risk assessment due to emissions from medical waste incinerator in Malaysia. Journal of Teknology. 2016;78(8-3):109-15.

21. Li J, Lv Z, Du L, Li X, Hu X, Wang C, et al. Emission characteristic of polychlorinated dibenzo-p-dioxins and polychlorinated dibenzofurans (PCDD/Fs) from medical waste incinerators (MWIs) in China in 2016: A comparison between higher emission levels of MWIs and lower emission levels of MWIs. Environmental Pollution. 2017;221:437-44.

22. Alvim-Ferraz MC, Afonso SA. Incineration of healthcare wastes: Management of atmospheric emissions through waste segregation. Waste Management. 2005;25(6 SPEC. ISS.):638-48.

23. Lee WJ, Liow MC, Hsieh LT, Chen TJ, Tsai PJ. Impact of polycyclic aromatic hydrocarbon emissions from medical waste incinerators on the urban atmosphere. Journal of the Air & Waste Management Association. 2003 Sep 1;53(9):1149-57.

24. Jang YC, Lee C, Yoon OS, Kim H. Medical waste management in Korea. Journal of environmental management. 2006;80(2):107-

15.

25. Alvim-Ferraz MC, Afonso SA. Incineration of different types of medical wastes: Emission factors for gaseous emissions. Atmospheric Environment. 2203;37(38):5415-22.

26. Chen T, Li X, Yan J, Jin Y. Polychlorinated biphenyls emission from a medical waste incinerator in China. Chen T, Li X, Yan J, Jin Y. Polychlorinated biphenyls emission from a medical waste incinerator in China. Journal of hazardous materials. 2009;172(2-3):1339-43.

27. Szewczyńska M, Dobrzyiiska E, Posniak M. Application of HPLC to determination of aldehydes, ketones and polycyclic aromatic hydrocarbons in air samples collected in uncontrolled combustion sources. Chemia Analityczna. 2009;54(3):349-66.

28. Suryawan IW, Prajati G, Afifah AS. Bottom and fly ash treatment of medical waste incinerator from community health centres with solidification/stabilization. InAIP Conference Proceedings 2019 Jun 26 (Vol. 2114, No. 1, p. 050023). AIP Publishing LLC.

29. Li YM, Wang CF, Wang LJ, Huang TY, Zhou GZ. Removal of heavy metals in medical waste incineration fly ash by Na2EDTA combined with zero-valent iron and recycle of Na2EDTA: Acolumnar experiment study. Journal of the Air & Waste Management Association. 2020 Sep 1;70(9):904-14.

30. Rahim FL, Hassim MH, Mokhtar MM. Environmental assessment of ashes generated from medical waste incineration. Chemical Engineering Transactions. 2015;45:1699-704.

31. Anastasiadou K, Christopoulos K, Mousios E, Gidarakos E. Solidification/stabilization of fly and bottom ash from medical waste incineration facility. Journal of hazardous materials. 2012;207-208:165-70.

32. Mao IF, Chen CN, Lin YC, Chen ML. Airborne particle $PM_{2.5}/PM_{10}$ mass distribution and particle-bound PAH concentrations near a medical waste incinerator. Atmospheric Environment. 2007;41(11):2467-75.

33. Zakaria AM, Labib OA, Mohamed MG, Waffa I, Hussein AH. Assessment of combustion products of medical waste incinerators in Alexandria. The Journal of the Egyptian Public Health Association (JEPHAss.). 2005;80(3-4):405-31.

34. Wheatley A, Sadhra S. Carcinogenic risk assessment for emissions from clinical waste incineration and road traffic. International journal of environmental health research. 2010;20(5):313-27.

35. Gerasimov GY. Comparative analysis of PCDD/Fs formation during pyrolysis and incineration of medical waste. InIOP Conference Series: Earth and Environmental Science 2019 Jun 1 (Vol. 272, No. 2, p. 022116). IOP Publishing.

36. Ferraz MA, Cardoso JB, Pontes SR. Concentration of atmospheric pollutants in the gaseous emissions of medical waste incinerators. Journal of the Air & Waste Management Association. 2000;50(1):131-6.

37. Yang Y, Han J, Yin W, Fu J, Zhang S, Qing X, et al. Concentrations distribution of PCDD/Fs and its health risk assessment in ambient air around a medical waste incinerator (MWI). Huanjing Kexue Xuebao. 2019;39(12):4215-25.

38. Chen T, Zhan MX, Yan M, Fu JY, Lu SY, Li XD, et al. Dioxins from medical waste incineration: Normal operation and transient conditions. Waste Manage Res. 2015;33(7):644-51.

39. Chen T, Zhan MX, Lin XQ, Fu JY, Lu SY, Li XD. Distribution of PCDD/Fs in the fly ash and atmospheric air of two typical hazardous waste incinerators in eastern China. Environmental Science and Pollution Research. 2015;22(2):1207-14.

40. Yan M, Li X, Chen T, Lu S, Yan J, Cen

K. Effect of temperature and oxygen on the formation of chlorobenzene as the indicator of PCDD/Fs. Journal of Environmental Sciences. 2010;22(10):1637-42.

41. Karademir A. Health risk assessment of PCDD/F emissions from a hazardous and medical waste incinerator in Turkey. Environmental International. 2004;30(8):1027-38.

42. Coutinho M, Pereira M, Rodrigues R, Borrego C. Impact of medical waste incineration in the atmospheric PCDD/F levels of Porto, Portugal. Science of the Total Environment. 2006;362(1-3):157-65.

43. Kharat DS, Sharma MK. Monitoring of a common biomedical waste incineration facility-a case study. Int J ChemTech Res. 2016;9(1):179-84.

44. Liu W, Tian Z, Li H, Xie H, Xiao K, Li C, et al. Mono- to Octa-Chlorinated PCDD/Fs in Stack Gas from Typical Waste Incinerators and Their Implications on Emission. Environmental science & technology. 2013;47(17):9774-80.

45. Adesina OA, Sonibare JA, Diagboya PN, Adejuwon A, Famubode T, Bello JO. Periodic characterization of alkyl-naphthalenes in stack gas and ambient air around a medical waste incinerator. Environmental Science and Pollution Research. 2017 Sep;24(27):21770-7.

46. Adesina OA, Sonibare JA, Diagboya PN, Adeniran JA, Yusuf RO. Spatiotemporal distributions of polycyclic aromatic hydrocarbons close to a typical medical waste incinerator. Environ Sci Pollut Res. 2018;25(1):274-82.

47. Gao H, Ni Y, Zhang H, Zhao L, Zhang N, Zhang X, et al. Stack gas emissions of PCDD/Fs from hospital waste incinerators in China. Chemosphere. 2009;77(5):634-9.

48. Su SS, Lu Y, Hui Y. The study of PCDD/Fs distribution in a medical waste incinerator. InAdvanced Materials Research 2012 (Vol. 356, pp. 2643-2646). Trans Tech Publications Ltd.

49. Bujak J. Thermal treatment of medical waste in a rotary kiln. Journal of Environmental Management. 2015;162:139-47.

50. Hoyos A, Cobo M, Aristizabal B, Cordoba F, de Correa CM. Total suspended particulate (TSP), polychlorinated dibenzodioxin (PCDD) and polychlorinated dibenzofuran (PCDF) emissions from medical waste incinerators in Antioquia, Colombia. Chemosphere. 2008;73(1):S137-S42.

51. Sun J, Tang J, Chen Z, Nie J, Zhang S, Li J. PCDD/Fs profile in ambient air of different types factories and human health risk assessment in Suzhou of Jiangsu province, China. Atmospheric Pollution Research. 2017;8(1):74-9.

52. Xuan Z, Bi C, Li JF, Nie JH, Chen ZH. Source contributions to total concentrations and carcinogenic potencies of polychlorinated dibenzo-p-dioxins and polychlorinated dibenzofurans (PCDD/Fs) in ambient air: a case study in Suzhou City, China. Environmental Science and Pollution Research. 2017;24(30):23966-76.

53. Dallarosa JB, Mônego JG, Teixeira EC, Stefens JL, Wiegand F. Polycyclic aromatic hydrocarbons in atmospheric particles in the metropolitan area of Porto Alegre, Brazil. Atmospheric Environment. 2005 Mar 1;39(9):1609-25.

54. Zakaria A, Labib O. Evaluation of emissions from medical waste incinerators in Alexandria. The Journal of the Egyptian Public Health Association. 2003;78(3-4):225-44.

55. Xie R, Li WJ, Li J, Wu BL, Yi JQ. Emissions investigation for a novel medical waste incinerator. Journal of hazardous

materials. 2009;166(1):365-71.

56. Graney JR, Dvonch JT, Keeler GJ. Use of multi-element tracers to source apportion mercury in south Florida aerosols. Atmos Environ. 2004;38(12):1715-26.

57. Murray M, Holmes SA. Assessment of mercury emissions inventories for the Great Lakes states. Environmental research. 2004;95(3):282-97.

58. Thi HN, Thu TNT, Hai LP, Thanh HN, Viet HC, Thi HC, et al. Emission of Unintentionally Produced Persistent Organic Pollutants from Some Industrial Processes in Northern Vietnam. Bulletin of environmental contamination and toxicology. 2019;102(2):287-96.

59. Sukandar, Padmi T, Tanaka M, Aoyama I. Chemical stabilization of medical waste fly ash using chelating agent and phosphates: Heavy metals and ecotoxicity evaluation. Waste Management. 2009;29(7):2065-70.

60. Tan Z, Xiao G. Leaching characteristics of fly ash from Chinese medical waste incineration. Waste management and research. 2012;30(3):285-94.

61. Pham MT, Hoang AQ, Nghiem XT, Tu BM, Dao TN, Vu DN. Residue concentrations and profiles of PCDD/Fs in ash samples from multiple thermal industrial processes in Vietnam: Formation, emission levels, and risk assessment. Environmental Science and Pollution Research. 2019 Jun;26(17):17719-30.

62. Akyıldız A, Köse ET, Yıldız A. Compressive strength and heavy metal leaching of concrete containing medical waste incineration ash. Construction and Building Materials. 2017;138:326-32.

63. Liu F, Liu HQ, Wei GX, Zhang R, Liu GS, Zhou JH, et al. Detoxification of medical waste incinerator fly ash through successive flotation. Separation Science and Technology. 2019;54(1):163-72.

64. Kim L, Catrina GA, Stanescu B, Pascu LF, Gheorghita T, Manolache D. The chemical fractions and leaching of heavy metals in ash from medical waste incineration using two different sequential extraction procedures. Revista de Chimie. 2019;70(1):269-74.

65. Bo D, Zhang FS, Zhao L. Influence of supercritical water treatment on heavy metals in medical waste incinerator fly ash. Journal of hazardous materials. 2009;170(1):66-71.

66. Wei GX, Liu HQ, Liu F, Zeng TT, Liu GS, Zhang R, et al. Effect of pH on the flotation performance of incinerator fly ash. Separation Science and Technology. 2019;54(11):1829-41.

67. Adama M, Esena R, Fosu-Mensah B, Yirenya-Tawiah D. Heavy metal contamination of soils around a hospital waste incinerator bottom ash dumps site. Journal of environmental and public health. 2016;2016.

68. Wu HL, Lu SY, Yan JH, Li XD, Chen T. Thermal removal of PCDD/Fs from medical waste incineration fly ash-Effect of temperature and nitrogen flow rate. Chemosphere. 2011;84(3):361-7.

69. Wang YF, Wang LC, Hsieh LT, Li HW, Jiang HC, Lin YS, et al. Effect of Temperature and CaO Addition on the Removal of Polychlorinated Dibenzo-p-dioxins and Dibenzofurans in Fly Ash from a Medical Waste Incinerator. Aerosol and Air Quality Research. 2012;12(2):191-9.

70. Liu HQ, Liu F, Wei GX, Zhang R, Zhu YW. Effects of surfactants on the removal of carbonaceous matter and dioxins from weathered incineration fly ash. Aerosol and Air Quality Research. 2017;17(9):2338-47.

71. Allawzi M, Al-harahsheh M, Allaboun H. Characterization and Leachability Propensity of Bottom Ash from Medical Waste Incineration. Water, Air, & Soil Pollution.

2018 May;229(5):1-3.

72. Ibanez R, Andres A, Viguri JR, Ortiz I, Irabien JA. Characterisation and management of incinerator wastes. Journal of hazardous materials. 2000;79(3):215-27.

73. Chen Y, Zhao R, Xue J, Li J. Generation and distribution of PAHs in the process of medical waste incineration. Waste Management. 2013;33(5):1165-73.

74. Alawi MA, Al-Mikhi NE. Levels of polycyclic aromatic hydrocarbons in waste incineration ash of some Jordanian hospitals using GC/MS. The journal of solid waste technology and management. 2016;42(4):298-307.

75. Zhao L, Zhang FS, Chen M, Liu Z, Wu DBJ. Typical pollutants in bottom ashes from a typical medical waste incinerator. Journal of Hazardous Materials. 2010;173(1-3):181-5.

76. Zhao L, Zhang FS, Hao Z, Wang H. Levels of polycyclic aromatic hydrocarbons in different types of hospital waste incinerator ashes. Science of the total environment. 2008;397(1-3):24-30.

77. Arar S, Alawi MA, Al-Mikhi NE. Levels of PCDDs/PCDFs in waste incineration ash of some Jordanian hospitals using GC/MS. Toxin Reviews. 2019 Dec 2:1-0.

78. Pan X, Yan J, Xie Z. Detoxifying PCDD/Fs and heavy metals in fly ash from medical waste incinerators with a DC double arc plasma torch. Journal of Environmental Sciences. 2013;25(7):1362-7.

79. Yan M, Li XD, Lu SY, Chen T, Chi Y, Yan JH. Persistent organic pollutant emissions from medical waste incinerators in China. Journal of Material Cycles and Waste Management. 2011;13(3):213-8.

80. Nguyen TT, Hoang AQ, Nguyen VD, Nguyen HT, Van Vu T, Vuong XT, et al. Concentrations, profiles, emission inventory, and risk assessment of chlorinated benzenes in bottom ash and fly ash of municipal and medical waste incinerators in northern Vietnam. Environmental Science and Pollution Research. 2021 Mar;28(11):13340-51.

81. Kumar R, Patel DK, Kumar R. A survey of trace metals determination in hospital waste incinerator in Lucknow City, India. Online Journal of Health and Allied Sciences. 2004;3(2).

82. Jin J, Li X, Chi Y, Yan J. Heavy metals stabilization in medical waste incinerator fly ash using alkaline assisted supercritical water technology. Waste management & research. 2010;28(12):1133-42.

83. Ni M, Du Y, Lu S, Peng Z, Li X, Yan J, et al. Study of ashes from a medical waste incinerator in China: Physical and chemical characteristics on fly ash, ash deposits and bottom ash. Environmental Progress & Sustainable Energy. 2013;32(3):496-504.

84. Valavanidis A, Iliopoulos N, Fiotakis K, Gotsis G. Metal leachability, heavy metals, polycyclic aromatic hydrocarbons and polychlorinated biphenyls in fly and bottom ashes of a medical waste incineration facility. Waste Management Research. 2008;26(3):247-55.

85. Racho P, Jindal R. Heavy metals in bottom ash from a medical-waste incinerator in Thailand. Practice Periodical of Hazardous, Toxic, and Radioactive Waste Management. 2004;8(1):31-8.

86. Zhao L, Zhang FS, Wang K, Zhu J. Chemical properties of heavy metals in typical hospital waste incinerator ashes in China. Waste Management. 2009;29(3):1114-21.

87. Anjum F, Shahid M, Bukhari SA, Potgieter JH. Combined ultrasonic and bioleaching treatment of hospital waste incinerator bottom ash with simultaneous extraction of selected metals. Environmental technology. 2014;35(3):262-70.

88. Bakkali ME, Bahri M, Gmouh S, Jaddi H, Bakkali M, Laglaoui A, et al. Characterization of bottom ash from two hospital waste incinerators in Rabat, Morocco. Waste Management and Research. 2013;31(12):1228-36.

89. Kougemitrou I, Godelitsas A, Tsabaris C, Stathopoulos V, Papandreou A, Gamaletsos P, et al. Characterisation and management of ash produced in the hospital waste incinerator of Athens, Greece. Journal of Hazardous Materials. 2011;187(1-3):421-32.

90. Xie Y, Zhu J. Leaching toxicity and heavy metal bioavailability of medical waste incineration fly ash. Journal of Material Cycles and Waste Management. 2013;15(4):440-8.

91. Meng B, Ma W-L, Liu L-Y, Zhu N-Z, Song W-W, Lo CY, et al. PCDD/Fs in soil and air and their possible sources in the vicinity of municipal solid waste incinerators in northeastern China. Atmos Pollut Res. 2016;7(2):355-62.

92. Singh S, Prakash V. Toxic environmental releases from medical waste incineration: A review. Environmental monitoring and assessment. 2007;132(1-3):67-81.

93. Al-Dabbas MA. The PCDD/PCDF Dioxin Releases in the Climate of Environment of Jordan in the Period (2000-2008). Journal of Thermal Science. 2010;19(2):182-92.

94. Wang LC, Lee WJ, Lee WS, Chang-Chien GP, Tsai PJ. Effect of chlorine content in feeding wastes of incineration on the emission of polychlorinated dibenzo-p-dioxins/dibenzofurans. Science of the total environment. 2003;302(1-3):185-98.

95. Choi KI, Lee SH, Lee DH. Emissions of PCDDs/DFs and dioxin-like PCBs from small waste incinerators in Korea. Atmospheric Environment. 2008;42(5):940-8.

96. Ferdowsi A, Ferdosi M, Mehrani Z, Narenjkar P. Certain hospital waste management practices in Isfahan, Iran. International journal of preventive medicine. 2012;3(4).

97. Yan JH, Zhu HM, Jiang XG, Chi Y, Cen KF. Speciation of Cd/Cu/Pb/Zn during medical waste incineration. Journal of Zhejiang University (Engineering Science).2008;42(10):1812-16.

98. Vremera R, Costinel D, Ionete RE, Titescu G. Overview on dioxins and furans atmospheric emissions in romania. Environmental Engineering and Management Journal (EEMJ). 2011;10(2):241-50.

99. Gautam V, Thapar R, Sharma M. Biomedical waste management: Incineration vs. environmental safety. Indian journal of medical microbiology. 2010;28(3):191-2.

100. Razif M. Impacts estimation of dioxin emission from management application of medical waste incinerator in community health centers and hospitals of Java Island, Indonesia. Pollution Research. 2018;37(1):16-24.

101. Barjoan EM, Doulet N, Chaarana A, Festraëts J, Viot A, Ambrosetti D, et al. Cancer incidence in the vicinity of a waste incineration plant in the Nice area between 2005 and 2014. Environmental research. 2020;188:109681.

102. Zhu J, Hirai Y, Sakai SI, Zheng M. Potential source and emission analysis of polychlorinated dibenzo-p-dioxins and polychlorinated dibenzofurans in China. Chemosphere. 2008;73(1):S72-S7.

103. Idris A, Saed K. Characteristics of slag produced from incinerated hospital waste. Journal of hazardous materials. 2002;93(2):201-8.

104. Levendis YA, Atal A, Carlson JB, Quintana MD. PAH and soot emissions from burning components of medical waste: examination/surgical gloves and cotton pads. Chemosphere. 2001;42(5-7):775-83.

105. Qing L. Formation of dioxin in a rotary

kiln medical waste incineration line. Chinese Journal of Environmental Engineering. 2013;7(2):743-6.

106. Tufail M, Khalid S. Heavy metal pollution from medical waste incineration at Islamabad and Rawalpindi, Pakistan. Microchemical Journal. 2008 Oct 1;90(1):77-81.