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Environmental Impact of Medical Waste Incineration - Literature Review

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ABSTRACT

The most commonly employed techniques for managing medical waste are thermal treatment (incineration, pyrolysis, and gasification) and sterilization (thermal or chemical disinfection). These methods are highly effective for managing medical waste with low pathogen loads. Incineration is a widely adopted technique in developed nations for managing most types of hazardous medical waste. It can completely eradicate pathogens and reduce waste weight by more than 70% (or 90% by volume). This review paper will examine and discuss the major challenges associated with medical waste incineration and their impacts on the environment, drawing on the latest research and studies. It will also outline effective solutions for mitigating the negative effects of incinerator contaminants on the surrounding environment.

Keywords: Medical Waste incineration, MBA, MFA, PAH, PCDD/Fs, PCB, Medical Waste management.

I. INTRODUCTION

Medical waste is a broad term that encompasses any waste generated by healthcare facilities, such as hospitals, clinics, dental practices, and laboratories, that may pose a risk to public health or the environment. It includes a wide range of materials, including sharps (needles, syringes, scalpels), infectious waste (tissues, blood, bodily fluids), pharmaceuticals, and hazardous chemicals. Improper management of medical waste can lead to serious consequences, including the transmission of infectious diseases, environmental pollution, and occupational hazards to healthcare workers and waste handlers.

In healthcare facilities across the globe, a substantial volume of potentially infectious and hazardous wastes is produced each year. Unfortunately, in many economically developing nations, the resources required to handle these wastes effectively are insufficient. Additionally, the majority of healthcare facility staff lack familiarity with appropriate waste management techniques. Consequently, the responsibility for waste management is often assigned to undereducated and untrained workers, who carry out their tasks without adequate guidance or protective measures [1]

Therefore, the proper handling and disposal of medical waste is critical for public health and environmental protection. Regulatory bodies have put in place regulations and guidelines to ensure that medical waste is handled, transported, and disposed of in a safe and environmentally sound manner. Healthcare facilities are responsible for implementing these regulations and guidelines and ensuring that medical waste is properly managed from its generation to its final disposal.

According to the World Health Organization (WHO), the majority of waste generated at healthcare facilities (about 85%) exhibits similarities to regular municipal solid waste. However, the remaining 15% is classified as hazardous due to its infectivity, toxicity, carcinogenicity, and radioactivity, necessitating specific handling and treatment [2]– [4]. Medical waste (MW) does not possess fixed and universally established definitions, given that its categorization differs based on the perspectives and economic situations prevailing in various countries and regions [5]. WHO has categorized medical waste into seven distinct groups, based on their properties and the associated level of risk they pose. [6]

Waste category	Description
Infectious waste	waste contaminated with blood and other body fluids (*i.e.,* from discarded diagnostic samples), cultures and stocks of infectious agents from laboratory work (*i.e.,* waste from autopsies and infected animals from laboratories), or waste from patients in isolation wards and equipment (*i.e.,* swabs, bandages, and disposable medical devices)
Pathological waste	human tissues, organs or fluids, body parts and contaminated animal carcasses
Sharps	syringes, needles, disposable scalpels, and blades, etc.
Chemicals	for example, solvents used for laboratory preparations, disinfectants, and heavy metals contained in medical devices (*i.e.,* mercury in broken thermometers) and batteries.
Pharmaceuticals	expired, unused and contaminated drugs and vaccines
Genotoxic waste	highly hazardous, mutagenic, teratogenic, or carcinogenic, such as cytotoxic drugs used in cancer treatment and their metabolites
Radioactive waste	such as products contaminated by radionuclides including radioactive diagnostic material or radio therapeutic materials; and non-hazardous or general waste: waste that does not pose any particular biological, chemical, radioactive, or physical hazard

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Several medical waste disposal methods are available, and the most appropriate method depends on the type and quantity of waste generated, as well as the location and regulations of the facility. Choosing the best medical waste treatment technology is a challenging decision-making task that involves analysing various alternatives and balancing conflicting criteria [7]. The decision-making approaches suggested in the proposal allow decision-makers to employ linguistic terms, thereby alleviating their cognitive burden during the evaluation process.[8]. Medical waste can be treated using several methods, such as thermal, chemical, radiation, biological, and mechanical treatments, with thermal treatment being the dominant method worldwide. The most employed thermal treatment methods for hazardous waste disposal are incineration and autoclaving [9].

Incineration	Burning medical waste at high temperatures to reduce the volume and eliminate pathogens. It is suitable for pathological and sharps waste and is considered the most effective method of medical waste disposal.
Autoclaving	Uses high-pressure steam to sterilize and decontaminate medical waste. The waste is loaded into a large autoclave chamber, and steam is injected to sterilize the waste.
Plasma Pyrolysis	utilizes a thermo-chemical process in the absence of oxygen to transform solid waste into energy. This innovative method offers an environmentally sustainable waste management option, resulting in minimal harmful emissions [10].
Chemical disinfection	Treating medical waste with disinfectants such as chlorine or hydrogen peroxide to eliminate pathogens. It is suitable for liquid and solid medical waste but is not as effective as incineration or autoclaving.
Microwave treatment	Uses microwave radiation to disinfect medical waste. It is suitable for small quantities of waste and can be used for sharps, plastics, and other non-infectious waste.
Landfill	The least desirable option for medical waste disposal as it poses a risk of environmental contamination. However, if the waste is non-infectious and has been treated appropriately, it may be disposed of in a landfill.

Incineration is the most utilized method for treating healthcare wastes [11]. So, the advantages and disadvantages of different technology are presented in Table 1 for a comprehensive comparison [12].

Table 1. Comparison of treatment technologies [10].

	Treatment Technologies				
	Incineration	Autoclave	Microwave	Plasma Pyrolysis	Landfilling
Advantages	-Accept the greatest variety of waste, -Treated waste is unrecognizable as ash, -Significant volume reduction, -Energy recovery, -Waste totally sterilized	-Environmentally sound, -Adopted for many years, -No hazardous emissions, -Low cost, -Technology is easily, -No pre-or-post treatment required	-Technology is easy, -Reduce volume by 80%, -Environmentally sound, -No liquid effluents,	-Suitable all types of wastes, -Consumes less space, -Environmentally sound, -Not require chimney, -Toxic residuals is	-Low cost, -Easy operation

			-The emissions are minimal	much below, -Not require segregation, -Energy recovery, -Reduce volume more than 99%	
Disadvantages	-Very expensive, -Acid gases in air emissions, -Heavy metals in ash residues, -Convert biological problem into potential air quality emission problems, -Major source of dioxin and furan emissions	-Need drying mechanism, -Foul odors, -Not suitable for all types of wastes, -Need a shredder to reduce the volume	-Cost is very high, -Not suitable for all types of wastes, -The shredder used is noisy -Offensive odors	-Requires technical persons, -Cost is very expensive	-Requires access to sanitary landfill, -Cause soil pollution, -water contamina tion,

The incineration method ensures the complete thermal destruction of all pathogens while simultaneously reducing the waste weight by over 70% (equivalent to 90% reduction in terms of their original volume). It proves to be suitable for various categories of medical waste, excluding specific types like radioactive materials and batteries, among others. Incinerators are equipped to manage a range of medical waste categories, encompassing cultures and infectious agents, pathological wastes, human blood waste, hypodermic needles, syringes, pasteur pipettes, broken glass, and scalpel blades, as well as contaminated animal carcasses and body parts. Additionally, they handle wastes originating from surgery or autopsy, medical, pathological, and pharmaceutical laboratories, dialysis waste, discarded medical equipment in contact with infectious agents, and biological waste or contaminated materials with human or animal blood, excretions, exudates, or secretions [13].

Erdogan and Yilmazoglu [14] conducted a study on the gasification characteristics of medical waste in an updraft plasma gasifier with the aim of addressing the need for proper disposal of medical waste in hospitals. The Covid-19 pandemic has underscored the importance of this issue, as the increasing amounts of medical waste produced have strained incineration facilities and storage areas. To mitigate this issue, gasification technologies have been proposed as a sustainable solution for converting medical waste to energy.

Three different medical waste samples and five different equivalence ratios were considered in this study to examine the effects of waste feeding rates on hydrogen (H_2) content and syngas production. Results revealed that an equivalence ratio of 0.1 yielded the best results for gasification of medical waste, producing up to 32.78% H_2, 25.37% CO, and 78.61% CGE. Moisture content was found to have a greater effect than carbon and hydrogen content on the gasification characteristics and H_2 production capabilities of the waste feedstock. The study also evaluated the correlation between temperature distribution and CO_2 distribution and found that the gasification characteristics of medical waste could be controlled by adjusting the distance between the gasification region and the syngas output.

The maximum H_2S mole fraction was found to be 0.6%. Furthermore, the use of plasma gasification technology for both the treatment of medical waste and the production of H_2 was found to be a promising solution, with the gasification characteristics capable of being enhanced by optimizing the exhaust pipe height of the gasifier. However, further studies are required to evaluate the formation of harmful substances inside the gasifier and to examine the effects of moisture content and ER values lower than 0.1. In conclusion, this study contributes to the development of sustainable solutions for the proper disposal of medical waste in hospitals by demonstrating the effectiveness of plasma gasification technology for converting medical waste to energy.

2. Challenges and Environmental Concerns of M W I

Medical waste incineration - M W I is an established method for waste disposal, but it comes with certain challenges and environmental concerns. While it effectively reduces pathogens and waste volume, there are drawbacks to consider. The primary concern lies in the emission of trace pollutants, such as heavy metals (cadmium, lead, mercury), polychlorinated dibenzo-p-dioxins (PCDD), and polychlorinated dibenzofurans (PCDF). These pollutants, especially in older plants, have not been adequately controlled in the past, leading to increased apprehension about their potential adverse effects on human health and the environment [15]. Communities near incineration facilities may be exposed to toxic emissions, impacting their well-being. Additionally, incineration is costly due to specialized equipment and maintenance requirements. Furthermore, although waste volume is reduced, the remaining ash may still contain hazardous substances. Properly assessing the advantages and drawbacks of incineration as opposed to alternative methods is essential in selecting the most suitable and sustainable approach for specific scenarios. Some reports indicate that waste incineration may lead to decreased greenhouse gas emissions under particular circumstances [16].

2.1 Environmental Contaminants and Impact of M W I

Medical waste incineration can result in various forms of pollution that need attention:

1. Air pollution: Incineration releases pollutants like dioxins, furans, heavy metals, and particulate matter into the air, which can lead to respiratory problems, cancer, and neurological damage.
2. Water pollution: Improper disposal of incineration ash can cause heavy metals and contaminants to leach into the soil and groundwater. Untreated wastewater release can also contribute to water pollution.
3. Land pollution: Proper disposal of incineration ash is necessary to prevent contamination of the surrounding soil and groundwater.
4. Noise pollution: The operation of incineration equipment and waste transportation can generate noise pollution.
5. Visual pollution: Medical waste incineration facilities may impact the aesthetic qualities of the surrounding area.

While modern incineration facilities employ advanced technologies to minimize emissions and pollution. The potential toxic effects of these pollutants on human health and the environment have raised significant public concern regarding the global sustainability of the waste incineration process [17]. Therefore, incineration should be considered alongside other disposal options, considering specific circumstances and available resources. Proper waste management practices, including waste reduction, segregation, and safe disposal, can help minimize pollution associated with medical waste incineration.

2.1.1 MBA & MFA

Medical waste incineration generates two types of hazardous ash byproducts, namely medical fly ash (MFA) and medical bottom ash (MBA). MFA is a fine powder containing harmful substances such as heavy metals, dioxins, and furans, which can cause environmental pollution and pose a risk to human health. MBA is a solid material that contains heavy metals, pathogens, and radioactive materials, which can also pose a risk to human health if not disposed of properly. Both MFA and MBA should be handled as hazardous waste and not disposed of in regular landfills or incinerated with other waste streams. MFA is typically treated separately from other ash residues by using cement or thermal solidification. MBA is cooled by quenching, then stored in closed drums or containers for safekeeping. Although heavy metals usually remain in both types of ash, mercury is an exception, which can escape as a vapor during incineration. Substantial amounts of both ferrous and non-ferrous metals can be extracted from bottom ash. A plant in Switzerland, employing a dry extraction process, recorded an average composition of 11% iron, 2.2% aluminum, 0.5% copper, and 0.003% gold in the bottom ash.[16]

AZAD et al. [18] carried out the possibility of removing the chromium from chrome tanned liquor by adsorption method using medical waste incineration (MWI) fly ash. Two different process parameters; adsorbent dosage and contact time, were studied by performing batch experiments in the laboratory. Up to 99.99% of chromium removal was achieved using MWI fly ash as an adsorbent. The optimum adsorbent dosage and contact time was found to be 5 g/L and 20 minutes respectively where 99.96% chromium was removed. Consequently, The Freundlich isotherm model and pseudo second order kinetic model was found to be more favorable models for chromium removal with medical waste incineration fly ash. Finally, the use of MWI fly ash as an adsorbent to remove chromium content from tannery wastewater could be considered as an effective solution to maintain a sustainable environment.

Wang et al. [19] the study explored the environmental characteristics, resource availability, and recovery method of medical waste incineration fly ash (MW-IFA) and medical waste plasma vitrification fly ash (MW-PFA) in China. Both types of fly ash were found to have high chloride levels and rich in zinc, indicating their potential for recovery. However, the calcium content of MW fly ash influenced its mineral composition and heavy metal leaching characteristics. High-calcium MW-IFA posed a lower risk of Zn leaching compared to low-calcium MW-IFA and MW-PFA. The resource availability of Zn in MW fly ash was measured using different methods and found to be similar.

The proposed MW fly ash dissolution and recovery (MWFADR) technology, combining water washing and acid leaching processes, was suggested for ZnO and crystal salt production. The technology was found to be an environmentally and economically sound solution for recovering Zn and Cl from MW fly ash. However, the applicability of the proposed technology at an industrial scale still needs further evaluation. The future focus of the study is to extend the Zn recovery technology to an industrial scale and investigate the environmental, economic, and social benefits of MW fly ash recycling through life cycle assessments and energy sustainability analysis.

Załuska et al. [20] Published an article examines the correlation between the amount of pollutants emitted from a medical waste incinerator plant and the number of COVID-19 infections in Podlaskie Voivodeship, Poland. The paper discusses the issues of medical waste management during the COVID-19 pandemic and thermal processing as a method of medical waste utilization. The study analyzes the emission of pollutants into the atmosphere during combustion and compares it with the number of COVID-19 cases in the same region to investigate how the pandemic affects the amount of medical waste generated and, consequently, the amount of pollutants emitted into the atmosphere. The analysis shows a statistically significant, moderate positive correlation between the amount of COVID-19 medical waste and the number of COVID-19 cases. Furthermore, there is a statistically significant moderate correlation between the number of COVID-19 cases and emissions of SO_2, NO_χ, and HCl.

This correlation finding highlights additional costs to the environment and public health as the number of COVID-19 cases increases, which can be taken into account for pandemic planning by governments in the future. The study concludes that a properly functioning medical waste incineration plant is crucial for human health and environmental cleanliness in terms of air protection. The analysis of pollutant emissions from the medical waste incineration plant shows that the plant disposes of waste properly, and the devices reducing the emission of pollutants operate efficiently and are compatible with the continuous monitoring system.

However, the COVID-19 pandemic has a moderate effect on the increase in air pollutant emissions from medical waste incineration plants in Podlaskie Voivodeship, Poland. Therefore, it is recommended to carry out an energy balance of the analyzed incineration plant and try to use the thermal energy generated during the incineration of medical waste, which would have a positive ecological effect.

Miao et al. [21] analyzed the MBA from MEI (mobile emergency incineration) applied in Huoshenshan Hospital, Wuhan, China, during the COVID-19 pandemic, using various analytical methods. The MBAs collected from separate batches revealed that the main compounds were similar, and some properties of MBAs vary with the incinerated waste components. The lack of detection of COVID-19 revealed that there was no COVID-19 virus in the three MBA samples. The properties of MBAs were influenced by the increased usage of polypropylene (pp) products. Because PP products were easier to incinerate thoroughly, MBAs had a finer particle size and potential risks to landfills and the atmosphere.

In addition, Ca compounds were the main components in MBA. The XRD analysis of MBAs showed that calcite and quartz are the main crystalline compounds, and XRF and ICP tests revealed that the major element was Ca due to the addition of $CaCO_3$ during the production of PP. Due to the presence of Na and K and the increased content of Ca in MBAs, MBAs were highly alkaline, and the leachability of heavy metals was decreased. Therefore, the leached heavy metal contents (via EN 12457–2, TCLP 1311 and HJ/T 299–2007) were below the limits in GB 18598–2019. However, because the pH of MBAs exceeded the limits of waste in flexible landfills (7.0–12.0), MBAs should be landfilled in a rigid landfill according to Chinese regulations.

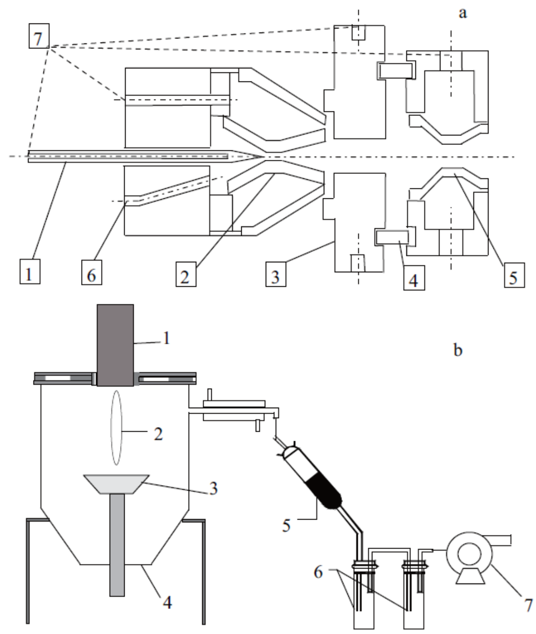
Ahmed et al. [22] the study conducted laboratory experiments to evaluate the feasibility of using medical waste incineration fly ash in cement as a construction material. The study analyzed the engineering properties of fly ash-cement matrix and the leaching potential of toxic heavy metals from the stabilized mix. The results indicated that the solidified matrix exhibited compressive strength from 3950 to 4980 psi when fly ash was mixed in varying proportions. The 28-day compressive strength decreased with the increase in fly ash content, but it met the minimum requirement for cement-mortar. The soundness test exhibited acceptable results for cement-mortar mixes having up to 15% fly ash. Final and initial setting times of cement generally increased with fly ash content, and the water requirement also increased with the increase in fly ash content. Based on the physical properties of the cement-mortar matrix, the study recommended that up to 10% (by weight) medical waste incineration fly ash can be incorporated for producing cement-mortar of optimum quality. The leaching behavior of several targeted heavy metals was analyzed using Toxicity Characteristics Leaching Procedure (TCLP) of fly ash and solidified fly ash-cement matrix, which showed that the leached concentrations of heavy metals were far below the EPA land disposal limits. The study concluded that heavy metals present in fly ash can be effectively immobilized when it is incorporated in cement-mortar matrix without significantly diminishing the engineering properties of cement-mortar. The study suggested that medical waste incineration fly ash incorporation into cement could be a promising avenue for waste management and successful recycling of waste in construction material.

Papamarkoua et al. [23] Describes the production of synthetic wollastonitic glass ceramics (WGCs) by combining medical wastes incinerator fly ash (MFA) with soda lime recycled glass (SLRG) and heating the mixture to 1300 °C, followed by re-crystallization in the range of 950 °C. The raw materials and the produced WGCs were analyzed chemically, mineralogically, and microstructurally. The leaching behavior of the WGCs was evaluated using the EN 12457-2 compliance leaching test.

The re-crystallization process led to the development of glass ceramics with two major crystalline phases: monoclinic wollastonite (b-$CaSiO_3$) and gehlenite ($Ca_2Al_2SiO_7$). The compressive and bending strength values varied from 190 to 194 MPa and 79–82 MPa, respectively. Although MFA exhibited high metals leaching values, indicating a hazardous waste, no trace elements were detected in the leachates of the WGCs. The leaching behavior of the original MFA, according to EN 12457-2 compliance test confirmed its hazardous nature, as the leaching values for Pb and Cl ions were found to be significantly higher than the accepted limits for hazardous wastes, according to the 2003/33/EC directive. On the other hand, no trace elements were detected in WGC leachates.

Tsakalou et al. [2] investigated the leachability and characterization of ashes produced from medical waste incineration and their glasses formed through vitrification with soda lime recycled glass. Two types of ashes were examined: Fly Ash (MFA) and Bottom Ash (MBA). The ashes were found to be hazardous waste, and if landfilling is necessary, they should be disposed of in accordance with regulation-prescribed waste dumps. However, the glasses produced from the ashes had low metal leachability values and were well below the corresponding regulatory limits. The study also explored the morphological characteristics of MFA and MBA and their behavior during leaching through Toxicity Characteristic Leaching Procedure and EN 12457-2 compliance leaching tests. The glass products had no trace elements detected in the leaching test. The study concluded that the vitrification of medical waste incineration ashes with SLRG could be a viable solution for their disposal.

Pan et al. [24] conducted a study to develop a direct current thermal plasma torch capable of converting fly ash from medical waste incinerators into safe slag. as shown in fig.1.



(a) plasma torch: 1–cathode, 2–anode I, 3-linked part, 4–insulated ring, 5–anode II, 6–gas entrance, 7–cooling water; (b) fly ash melting system: 1–plasma torch, 2–plasma arc; 3–crucible; 4–furnace; 5–XAD-2 resin; 6–absorption solution; 7–draught fan

Fig. 1 Schematic diagram of experimental set-up.

The researchers employed the toxicity characteristic leaching procedure to evaluate the leaching characteristics of heavy metals in fly ash and vitrified slag, while method 1613 of the US EPA was used to determine the content of polychlorinated dibenzo-p-dioxins and polychlorinated dibenzofurans (PCDD/Fs) in the fly ashes and slags. Two types of fly ash were used in the experiment: FA1, obtained from a medium-scale incinerator in Zhejiang Province, and FA2, obtained from a rotary kiln fluidized bed multi-stage pyrolysis incineration system. Both types of fly ash contained hazardous materials such as heavy metals and dioxins.

The experimental results demonstrated that the plasma melting process could decompose over 99% of PCDD/Fs in toxic equivalent quantity value and significantly reduce the leaching of heavy metals in the slag. The slag produced by this process had a homogeneous microstructure with high density. Prior to the melting process, the I-TEQ concentration of PCDD/Fs in FA1 and FA2 exceeded regulatory levels. However, after the plasma melting process, the destruction rate of PCDD/Fs in FA1 was found to be 99.72%, while that of FA2 was 98.57%. Moreover, the leaching of heavy metals in slag decreased considerably after the melting process, resulting in a volume reduction close to 78%. Hence, thermal plasma torch technology can be regarded as a promising alternative for the safe disposal of medical waste incinerator fly ash.

Bo et al. [25] highlighted on the usage of supercritical water (SCW) and SCW + H_2O_2 (SCWH) treatments to detoxify medical waste (MW) incinerator fly ashes. The study found that SCW treatment could transfer heavy metals in exchangeable and carbonate forms in the ashes into other relatively stable forms, while SCWH treatment could stabilize heavy metals in Fe–Mn oxides and residual fractions. However, the behavior of as was quite different from heavy metals, which could be leached out from residue fraction after SCW and SWCH treatments. The leached tended to absorb onto Fe–Mn oxides and organic matters under near neutral environment, but it could react with Ca2+ at lower pH, increasing the mobility of this element. Therefore, it is necessary to neutralize acidic ash to near neutral conditions before subjecting it to SCW and SCWH treatments to effectively stabilize hazardous elements in the ash. Consequently, it is believed that SCWH treatment is an effective alternative for hazardous elements detoxification in MW fly ash. On the other hand, As could be extracted from F5 fraction after SCW and SCWH treatments and tended to absorb onto Fe oxide and organic matters under near neutral condition. Thus, it is necessary to neutralize the acidic ash to near neutral condition before subjecting it to SCW and SCWH treatments so as to stabilize as in the ash. It is concluded that SCWH treatment could not only decompose hazardous organic matters but also effectively detoxify heavy metals in fly ashes.

Ferraz and Afonso [26] discuss the need for air pollution control devices in hospital incinerators to protect public health. Suggest that emission factors (EF) can be used to estimate legal parameters, but the actual knowledge is scarce due to the lack of information about the incinerated waste composition. The paper reports the first EF estimated for CO, SO_2, NOx and HCl, associated with the incineration of medical waste, segregated in different types according to the classification of the Portuguese legislation. The results showed that those EF for the incineration of medical waste are strongly dependent on the incineration conditions or the waste characteristics. The results showed that the EF for CO, SO2, NOx and HCl are influenced by the incinerated waste composition, which is directly affected by the incinerated waste type, waste classification, segregation practice and management methodology.

The usefulness of EF is doubtful when they are not associated with the composition of the incinerated mixture. A correspondence between the different waste classifications that are being used is not always possible. The legal limit for pollutant concentrations could be obeyed for NOx. However, the concentrations were higher than the limit for CO (11–24 times), SO2 (2–5 times), and HCl (9–200 times), confirming that air pollution control devices must be used to protect human health. The small heating value of medical wastes with compulsory incineration, when collected using a rigorous segregation practice, required the utilization of an auxiliary fuel amount for incineration 35 times higher than for the other waste types, which affects pollutant emissions of CO, NOx and SO2 (28%, 20% and practically 100% of the respective emitted amounts were related with fuel combustion). Nevertheless, the incineration of those wastes led to the smallest amount of emitted pollutants and the emitted amount of SO2 and NOx reduced to 93% and the emitted amount of CO and HCl to more than 99%, enhancing how important is the implementation of rigorous segregation practices and adequate methodologies of waste management.

2.1.2 Polychlorinated Biphenyls (PCBs)

PCBs can be released into the environment during medical waste incineration, as they are formed when chlorine-containing materials are burned at high temperatures. Medical waste, such as plastic containers and syringes, often contains chlorine-based compounds, which can lead to the formation of PCBs during incineration. PCBs are highly toxic and can cause a range of health problems, including developmental delays, neurological damage, and cancer. They can also accumulate in the fatty tissues of animals and humans, posing a risk to those who consume contaminated food.

Chen et al. [27] conducted an investigation on the emission of polychlorinated biphenyls (PCBs) and World Health Organization toxic equivalent concentrations (WHO-TEQ) in flue gas from a medical solid waste incinerator. The results showed that the total concentration of PCBs in the flue gas ranged from 138.01 to 855.35 nanograms per cubic meter (ng/Nm^3), while the WHO-TEQ concentration ranged from 0.046 to 0.549 nanograms TEQ per cubic meter (ng TEQ/Nm^3). Among the dioxin-like PCBs, PCB-77 was the most abundant, contributing 16% to 24% of the total concentration. Mono-chlorobiphenyls (mono-CBs) had the highest ratio among PCB homologues, ranging from 25% to 48%, with a mean value of 36%. The total mean concentration of mono- to tetra-CBs was over 90% of the total PCB concentration, indicating that the lower chlorinated PCBs were dominant in the flue gas samples.

PCB-126 was the most significant congener, accounting for more than 96% of the WHO-TEQ values in all conditions. The study also tested three inhibitors, sulfur, urea, and ammonium sulfate, to investigate their effectiveness in preventing PCB formation. Under condition 4, the mixture of urea and ammonium sulfate exhibited a stronger inhibitory effect on PCB formation, with a ratio of (S + N)/Cl = 1.3 of the fuel, leading to reductions in total PCBs and PCBs TEQ concentrations by up to 84% and 92%, respectively. The study also assessed the efficiency of the bag filter in removing the total PCBs and PCBs TEQ concentrations under two conditions. The results showed that the removal efficiency for total PCBs concentration and PCBs TEQ ranged from 69% to 86% and from 85% to 94%, respectively.

2.1.3 Heavy Metals

During medical waste incineration, heavy metals such as lead, cadmium, mercury, and arsenic can be released into the air as particulate matter or as vapor. These heavy metals can then be transported over long distances and deposit onto soil and water bodies, contaminating the environment and posing a risk to human health. Exposure to heavy metals can cause a range of health problems, including damage to the nervous system, kidney damage, developmental delays, and cancer. Children and pregnant women are particularly vulnerable to the toxic effects of heavy metals. To minimize the release of heavy metals and other harmful chemicals during medical waste incineration, it is important to use appropriate waste management practices, such as separating and properly disposing of hazardous materials, and utilizing advanced incineration technologies that are designed to minimize emissions. Additionally, efforts should be made to reduce the use of heavy metals in medical equipment and other industries to prevent their release during incineration.

Adu et al. [28] present an effective study of A novel gas filtering unit designed and fitted on an existing medical waste incinerator as one of the Air Pollution control devices APCD uses to clean the upcoming hazardous smoke. By using three powdered activated charcoal filter beds as adsorbent material was able to remove different congeners of organic pollutants, namely polychlorinated biphenyls PCBs to extents ranging from 2% to about 72 %. Through the study, the results showed that about 2.17 kg PM - particulate matter is released per cycle of incineration produced by this incineration with a 1.5 kg/bed/day hospital waste generation rate. This is quite considerable and should be adopted into the air pollution control techniques. Finally, it is mandatory to establish further studies using this gas filter to evaluate its effectiveness at removing dioxins and furans (PCDDs/PCDFs) from the smoke.

Xie and Zhu [29] Discussed and pointed out that the Self-propagating high temperature reaction SHR is a reliable technique for the detoxification of the heavy metals in MWIFA. The toxicity characteristic leaching procedure TCLP shows that the fly ash leaching concentration of Pb, Cd exceeds the toxicity regulation level of Hazardous Waste Characteristics, and the Cu and Zn are with relatively high environmental risk too. But for the SHR product, Cu, Pb, Cd are not detectable in the leachate. The detoxification was attributed to the solidification and the evaporation of heavy metals. The un-volatilized parts of heavy metal transform into Fe-Mn oxides, organic matter bound and residual forms from exchangeable and carbonates phase, which are stable in acid environment. In addition, the X-ray diffraction XRD and Scanning electron microscope SEM results indicated that MWIFA was melted and turned into melt inclusion. The degree of crystallization drops to 18% from the origin 46% illustrated the vitrification of the MWIFA. Heavy metals were mounted in the silicate framework, which led to the tremendous decrease in leaching concentration.

Anastasiadou et al. [30] Studied the stabilization/solidification treatment process for the fly and bottom ash to reduce the leachability of the heavy metals present in these materials regarding dispose them safely in non-hazardous landfills, or even to reuse these materials in the construction industry. By increasing the mechanical characteristics of the bottom ash using different amounts of Ordinary Portland Cement (OPC) as a binder. The solidified matrix showed that the cement can immobilize the heavy metals found in fly and bottom ash. Compressive strength tests, performed on the stabilized material after 28 days of solidification, The strength decreased as the percentage of cement loading was reduced; the compressive strength was 2.52–12.7MPa for 60% cement mixed with 40% fly ash and 6.62–16.12MPa for a mixture of 60% cement and 40% bottom ash. The compressive strength reduced to 0.55–1.30MPa when 30% cement was mixed with 70% fly ash, and to 0.90–7.95MPa when 30% cement was mixed with 70% bottom ash, respectively. More tests are needed to study the long-term behavior (more than 1 year) of solidified samples to evaluate possible changes in the matrix and leachability of heavy metals.

Javied et al. [31] investigate the concentration of heavy metals remained in ash of the incinerated waste from three hospitals of Islamabad and Rawalpindi. The waste is segregated into 3 categories as infectious, non-infectious and sharps. The concentration of Cd, Cr, Cu, Pb and Zn was found using FAAS (flame atomic absorption spectrometer). The amount of these metals varied from day to day, hospital to hospital, and incinerator to incinerator depending upon the medical waste generated in the hospitals. The main source of these metals in the incinerated ash was the presence of PVC (poly vinyl chloride) material in the waste. A wide variation in concentration of metals was due to diversity in the initial waste composition, design of the incinerator, and operating conditions. In some of the samples, the concentration of Pb was exceptionally higher than the standard value of EPA Canada. The concentration of other samples was within the limits. If incineration is the only choice for management of medical waste, then the newly generated incinerated waste of gases, fly and bottom ashes should be disposed properly to control environmental pollution. Some alternate methods less hazardous than incineration should also be explored.

Xiea et al. [32] A novel incinerator is proposed for better utilization of energy of the incineration process. Its originality is essentially due to combining a feeder, a rotary grate, a cylindrical gasifier, and a "coaxial" secondary combustion chamber into a unique unit as shown in Fig.2.

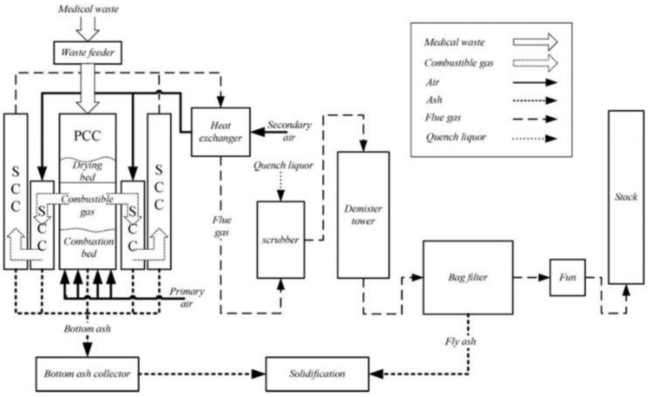


Fig.2 Main components of the incineration system

A full-scale trial of the novel incinerator with air pollution control devices (APCD) was carried out from March to May 2008 to investigate how the distinct configuration influenced the incineration process. During the experiment, it was found that the maximum measured level of PM in the inlet of the stack was 32mg/m³; CO was 63mg/m³; SO2 was 9.3mg/m³; NOX was 91mg/m³; HCl was 8.7mg/m³; and HF was 0.72mg/m³. All these pollutant levels belonged to the acceptable ranges set by Chinese and U.S. EPA, which confirmed that the novel installation effectively treated medical waste and produced stabilized product. The heavy metal in fly ash such as Cd and as still exceeded the limits at the stable running condition, implying that fly ash needed detoxification for its long-term storage on land. The evaluation of the heavy metals in flue gas and ash furnished an early approach to the assessment of their environmental impact. The total toxicity equivalent concentration (TEQ) value of PCDD/Fs in stack was 0.093 ng/m³, which was below the criteria. The TEQ tests also showed the emission of PCDD/Fs from this novel plant could be contributor of the higher chlorinated congeners of PCDD/Fs. Results from testing the novel medical waste incinerator confirmed that this technology has a good suitability for neutralization of medical wastes and purification of flue gases.

2.1.4 PCDD/FS

Dioxins, specifically polychlorinated dibenzo-p-dioxins, and polychlorinated dibenzofurans (PCDD/PCDFs) are dangerous and long-lasting organic pollutants that are produced during medical waste incineration. Medical waste contains chlorine-based compounds that can form dioxins when burned at high temperatures. Studies have indicated that exposure to PCDDs, PCDFs, can result in various health risks, including their contribution to cancer development, immunological disorders, teratogenic effects (birth defects), reproductive issues, and neuroendocrine disorders. These adverse health effects make these compounds a significant concern for public health and environmental safety[33]. To prevent their formation and release, proper waste management practices and advanced incineration technologies should be used, and the use of chlorine-containing materials in medical waste and other industries should be reduced. Incineration can create hazardous pollutants, including persistent organic pollutants (POPs) such as PCDDs/PCDFs, which are highly toxic and regulated worldwide due to their persistence in the environment and potential harm to human health. PCDDs/PCDFs are carcinogenic pollutants that can damage the immune system even at low concentrations. Medical waste incinerators generate the most PCDDs/PCDFs as they contain more chlorinated plastic waste than industrial or domestic waste. Chlorinated plastic waste from the incineration process is a precursor to PCDDs/PCDFs. Although current air pollution control devices (APCDs) can reduce PCDDs/PCDFs, complete removal using present technology is not yet possible.

Zhang et al. [34] examined the emission of pollutants during medical waste incineration using a pilot-scale vortexing fluidized-bed incinerator (VFBI) and analyzed the effects of various operating parameters. The study found that increasing the feeding interval reduced pollutant emissions due to the decreased bed temperature and prolonged residence time. The addition of calcium carbonate decreased gaseous pollutant emissions but increased the concentration of toxic polychlorinated dibenzo-p-dioxins and polychlorinated dibenzo-furans (PCDD/Fs) in fly ash. The concentration of NO and SO2 decreased while CO concentration increased with increasing chlorine content in the medical waste. The threshold value of the chlorine content for PCDD/Fs generation was about 1%, with a higher formation rate of PCDDs at lower chlorine content. The formation rate of PCDFs exceeded that of PCDDs when the chlorine content exceeded the threshold value of 1%, leading to increased concentrations of both pollutants due to increased CO concentration. The study highlights the importance of considering operating parameters and waste composition in medical waste incineration to minimize pollutant emissions.

Yoon et al. [35] measured toxic polychlorinated dibenzo-p-dioxins (PCDDs) and polychlorinated dibenzofurans (PCDFs) in stack gas samples from 19 medical waste incinerators in South Korea. The study found that the average concentrations of the sum of 17 toxic PCDD/PCDF congeners emitted from the medical waste incinerators ranged from 0.153 to 101.9 ng/Sm^3. Based on the World Health Organization toxic equivalency factor, they ranged from 0.007 to 5.437 ng TEQ/Sm^3. The congener patterns of PCDDs/PCDFs were described using principal component analysis and presented four patterns. Four incinerators had emissions above the dioxin emission standards, likely due to poor operation, while other factors such as the type of incinerator/operation, capacity, APCDs, and start date were not found to be significantly related to the high concentrations of PCDDs/PCDFs. Overall, the study provides useful information for the regulation of PCDDs/PCDFs from medical waste incinerators in South Korea.

Mukherjee et al. [36] discusses the problem of increasing waste generation in society and the need to reduce the amount of waste generated. Incineration is a commonly used technology to reduce waste, but it has the drawback of emitting harmful dioxins and furans in flue gas, which can cause serious health effects. Various methods are available to treat flue gas emissions, but this paper suggests a cost-effective, efficient, and long-lasting method to treat the flue gas and reduce the concentration of dioxins and furans effectively. The paper reviews the current views on minimizing dioxins and benzo-furans in different types of incineration systems, including municipal solid waste, hazardous solid waste, and biomedical waste. The paper discusses the formation mechanism, sources, and precursors of PCDD/Fs formation during the combustion process and presents various techniques established in the past twenty years to remove dioxins and furans. The paper recommends a hybrid method that combines good combustion practices with end-of-pipe treatment options to secure a sustainable future for incinerators and dioxin removal technologies. The findings of this paper will help stakeholders in decision-making processes for waste management and set future directions for innovative research to address associated challenges.

Lin et al. [37] a pilot-scale system with capacity 300 N m^3 h^{-1} was situated at the bypass of an actual hazardous waste incinerator (HWI) and tested to reduce the emission of PCDD/Fs. Activated carbon was used as a medium to adsorb SO_2 from flue gas and release it again at the higher temperature of filtered ash detoxification to achieve SO_2 circulation in the system.

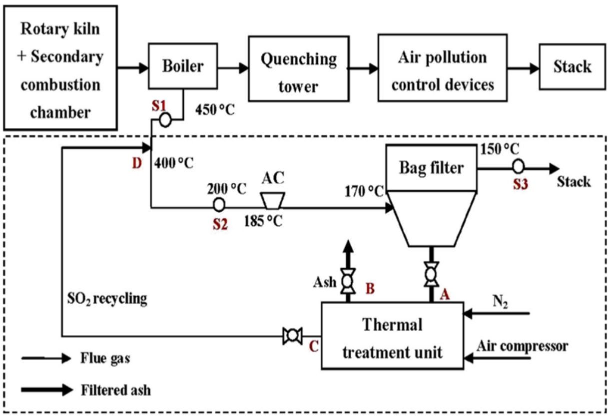


Fig. 3 Flow diagram of the pilot-scale SCS in the HWI.

Experimental results indicated that the system could maintain high SO_2 concentration accumulation of more than 300 mg N m^{-3} to reduce PCDD/Fs effectively. A reduction of more than 80% can be achieved for PCDD/Fs without other Sulphur compounds. When adding pyrite as additional Sulphur compound, the reduction of PCDD/Fs even reached 94% with low PCDD/Fs concentration in the flue gas of 0.13 ng TEQ N m^{-3}, close to the new national standard of 0.1 ng TEQ N m^{-3}. PCDFs contributed most to the concentration of PCDD/Fs, more than 65% in the flue gas and even 85% in the filtered ash. The congener profiles of PCDD/Fs trended towards low chlorinated species and became more obvious due to the chlorination suppression by SO_2 circulation in the flue gas and dechlorination by thermal treatment in the filtered ash. The SO_2 circulation technology provides significant guidelines for dioxin emission control in waste thermal treatment.

Rashida et al. [38] Used a liquid inhibitor (known as De-dioTM) on the emission of dioxin-furan from medical waste incineration plants. Various concentrations of De-dioTM solutions were tested on the medical waste incinerator combustion chamber with an injection flow rate of 1.5 L/min. The result showed that the De-dioTM was able to reduce or minimize the formation of dioxin furan to meet its regulatory limits. Therefore, the higher the concentration of De-dioTM solution, the lower the dioxin-furan emission was observed in the flue gas.

Yan et al. [39] discuss the use of nitrogen-containing compounds found in sewage sludge to inhibit the formation of polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD/Fs). The study observes that the gas produced during sludge drying can significantly reduce chlorobenzene and PCDD/Fs formation. Tests were conducted in a hospital waste incinerator and preliminary experiments were conducted to investigate the effect of sludge on PCDD/Fs emissions during co-pyrolysis/combustion of HW and sludge. The experiments revealed that sludge drying produces high amounts of NH3 and HCN, which can effectively suppress the formation of chlorinated organic pollutants. However, co-combustion/pyrolysis of PVC and dry sludge did not work as predicted, and further research is needed to investigate co-pyrolysis/combustion of HW and sludge in lab scale and real scale furnaces.

Wu et al. [40] investigated the effectiveness of thermal treatment under different temperature and nitrogen flow rate conditions for the removal of PCDD/Fs from medical waste incinerator fly ash. The results revealed that dechlorination and destruction reactions were significant factors in removing PCDD/Fs from fly ash, especially at temperatures above 350 ˚C, and PCDD/Fs were rarely desorbed into the flue gas. However, when the flow rate exceeded 4 cm s^{-1}, the destruction efficiency of PCDD/Fs decreased considerably, and P_5CDF, H_6CDF and H_7CDF were the main contributors to desorption into the flue gas. These findings suggest that flow rate should be considered when operating thermal treatment furnaces to remove PCDD/Fs from fly ash. Further studies are needed to understand the mechanism of PCDD/Fs desorption from fly ash and to optimize the destruction efficiency of PCDD/Fs during thermal treatment of fly ash from medical waste incineration systems.

Li et al. [41] A new MWI of China was started operation in May 2007, and implemented an advanced technology in the combustion and air pollution control system by the BAT/BEP guideline in August 2008. From 2007 to 2009, levels of PCDD/Fs were determined in soil collected in the vicinity of this MWI. The average concentration of PCDD/Fs in soil increased from 1.13 pg I-TEQ g^{-1} to 2.29 pg I-TEQ g^{-1} after 1 year operation of the MWI (2007–2008), and a marked decrease (0.50 pg I-TEQ g^{-1}) was observed during 2008–2009. In addition, the levels of PCDD/Fs (2009) were still higher than the values collected before the start-up operation of this plant (2007). With the MWI running, the PCDD/Fs emission will continue as well as the deposition and accumulation in soil. Consequently, it is necessary to control and reduce contaminant emission by stable combustion and advanced gas cleaning system with the enforcement of stricter pollutants emission standards.

Gunes [42] focusing on ÝZAYDAÞ and ÝSTAÇ incineration plants, the factors affecting the formation of polychlorinated dibenzo-p-dioxin (PCDD) and polychlorinated dibenzofuran (PCDF) in incineration plants were explained. Both the combustion units and the flue gas treatment units of both plants were examined, and how these units affect the formation of dioxin/furan compounds was explained. As a result of the examinations, it was determined that the combustion temperature and the residence time of the gas in the combustion chamber, especially in the second combustion chamber, were the most important factors for both the dioxin/furan compounds and the precursor compounds (chlorophenol, chlorobenzene, polychlorinated biphenyls) that enable the formation of these compounds to be broken down. Both plants use activated carbon adsorption process as dioxin/furan control unit. In ÝSTAÇ, the activated carbon injection method is applied and activated carbon is used in pulverized (powder) form. In ÝZAYDAÞ, fixed activated carbon columns containing granular activated carbon are used for adsorption. In this study, using some model equations explained in the literature, the optimum adsorbent amount was determined for both plants. The optimum dose for ÝSTAÇ was found to be 54.2 mg/m3, and the annual required amount was 5,213 tons/year. In ÝZAYDAÞ, the optimum dose for the adsorbent injection method was calculated as 0.01661 mg/m3 and the annual amount was 6,548 kg/year. The required amount in the fixed bed process was determined as 13 kg/year based on formula-based calculations. The formation of dioxin/furan emissions in incineration plants depends on providing complete combustion conditions (high temperature, sufficient residence time, turbulence) in the rotary kiln and second combustion chamber and operating appropriate flue gas control systems in the cold zone.

For the waste to stay in the combustion zone for a sufficient period, the rotary kiln and the second combustion chamber must be properly designed. Especially in incineration plants operated with modern technology, the formation of these compounds is controlled in the hot zone, and advanced flue gas control systems (activated carbon injection system, activated carbon reactor) are operated at low concentrations that may occur, removing them from the flue gas. Separating plastics and metals at the source, passing the waste through recycling units before it reaches the incineration plant and separating metals and plastics (for municipal waste incineration plants) can minimize dioxin/furan formation. The adsorbent injection method is more advantageous than other methods due to its ease of use, high removal efficiency, and low cost. The important thing in this process is to determine the optimum adsorbent dose. Excessive use of adsorbents has no effect on removal efficiency and bagging.

Yan et al. [43] tested three types of fly ashes collected from different medical waste incinerator types through using a mechanochemical MC treatment (which it is a non-combustion technology that requires no heating process or off-gas treatment, which is notable advantage over the conventional heating processes) grounding with and without calcium oxide (CaO) under atmospheric pressure. And the results indicate that.

- Under two test conditions of with and without CaO, PCDD/Fs contained in real fly ash both can be degraded by mechanochemical treatment,
- Under condition of blending with CaO, the degradation efficiency of PCDD/Fs increased with increasing ratio of CaO,
- The degradation efficiency of PCDD/Fs may increase with rotational speed increasing and
- The destruction and dechlorination are major mechanisms for PCDD/Fs degradation.

2.1.5 PAHs

Polycyclic aromatic hydrocarbons (PAHs) are a group of organic compounds that can be released during medical waste incineration. PAHs, comprising two or more fused benzene rings, result from the thermal decomposition and subsequent recombination of organic compounds. These environmental contaminants are formed through incomplete combustion at high temperatures (500–800 °C) or prolonged exposure of organic materials to lower temperatures (100–300 °C). PAHs are extensively distributed and have detrimental biological effects, exhibiting toxicity, mutagenicity, and carcinogenicity. Their widespread occurrence, resistance to degradation, tendency to accumulate in living organisms, and carcinogenic properties have raised significant environmental concern [44].

Qin et al. [45] investigated the use of porous alumina as a bed material to reduce the emission of polycyclic aromatic hydrocarbons (PAH) and monocyclic aromatic hydrocarbons (MAH) during medical waste incineration in a fluidized bed c
ombustor (FBC). The reduction mechanisms of PAH and MAH were studied using porous alumina, nonporous alumina, and silica sand as bed materials. The results showed that porous alumina had the highest reduction efficiencies for Σ MAH, Σ PAH, and Σ PAH toxic equivalent (TEQ) compared to silica sand under the same conditions. The reduction of PAH under porous alumina bed materials was due to three mechanisms: reduction in hydrocarbon evolution rate, increased absorption of gaseous hydrocarbon, and accelerated oxidation of gaseous hydrocarbon. The heat transmission, catalytic effect, and adsorption effect of porous alumina accounted for 22.8%, 29.2%, and 20.9% of the Σ PAH reduction, respectively. The use of porous alumina as a bed material could effectively reduce the emission of PAH and MAH during medical waste incineration.

Chen et al. [46] examines the generation of polycyclic aromatic hydrocarbons (PAHs) during the incineration of medical waste following an earthquake in China. Various incineration methods were used, and samples were collected from different sources. The analysis showed that fly ash had a significantly higher concentration of PAHs compared to bottom ash, particularly highly carcinogenic PAHs with four or more rings. PAHs were found to migrate from the incineration site to the surrounding environment through air and surface water pathways. The study also found that higher levels of oxygen and combustion temperature led to less generation of highly toxic PAHs. There was a positive correlation between total PAHs and total PCDD/Fs (dioxins), but not for their toxic equivalency. Based on the findings, the study recommends centralized disposal with strict pollution control measures, as well as exploring alternative methods like steam sterilization and chemical disinfection for medical waste treatment in emergencies.

Zhao et al. [47] Examined the heavy metals and polycyclic aromatic hydrocarbons (PAHs) in the bottom ashes which were collected from a typical medical waste incinerator. This type of waste ash may cause serious environmental problems if not properly managed. X-ray fluorescence spectroscopy results indicated that CaO, SiO_2 and Al_2O_3 were the main components of the bottom ash. High concentrations of metallic elements, such as Al, Cu, Fe, Mg, Mn, Pb, Ti, Zn and Cr were determined, and most of these metals were associated with the stable residual fraction. The results of US EPA leaching tests verified that all the metals met the standard leaching limits set by the US EPA. The ash could be recyclable as construction material, but it must be treated at high temperature (850–1000 ˚C) so as to destroy the PAHs before or during the recycling process.

2.2 M W Management

Medical waste management presents a major challenge, especially in handling hazardous materials involved in medical procedures, such as chemotherapy drugs and radioactive materials. As many countries handle hazardous and medical waste together with residential waste, creating a serious health risk for the public, waste handlers, and the environment[48]. Proper management of medical waste requires effective planning and coordination between healthcare facilities, waste management companies, and government agencies. This includes the development of waste management plans, training staff on proper handling techniques, ensuring that waste management companies have the necessary equipment and facilities, and enforcing regulations. The management of medical waste involves a complex process that considers various factors such as economics, technical considerations, environmental concerns, and social issues. The proper management of medical waste is crucial since they can directly and indirectly influence, health risks for both the public and the environment [49].

Chen et al. [50] discussed the key problems of the operation management of medical waste incineration facilities to improve their capability. On the basis of full use of the best available technology and puts forward appropriate countermeasures for the facilities operation around the source classification, process control, performance control, supervision and management and other aspects. This can be used by the medical waste incineration unit and the environmental protection departments at all levels for reference in the operation and supervision and management of medical waste incineration disposal facilities. The planning solves the construction problems of the hardware facilities, but the software problems such as the management to the facilities operation closely related to the pollution control must also be solved.

For the incineration of medical waste, we should, on one hand, based on the life cycle characteristics of the medical waste, start from the source to do well the waste reduction at the source and the source classification of the waste, and effectively cut off the production source of dioxins/furans and other pollutants; on the other hand, we should pay attention to the management to the operation of disposal facilities during disposal to fully promote the standardization of the facilities operation, standardize the operation management by improving the facilities of the disposal unit and actively apply the best environmental practice to ensure the attainment; third, we should start from the perspective of the whole process management, go to the process control from the end control and pay attention to the connection from the incineration materials control, automatic control of the process parameters to the local environmental supervision and management system.

Jiang et al. [51] classified the best available technology system of medical wastes centralized incineration facilities and analyzed the application of technique retrofit of medical waste centralized incineration facilities incorporated with case study. Highlighted all operation problems such as failure to continuous operation, system corrosion, high energy consumption, frequent equipment instrument damage, bad automatic control system performance, and on-line monitoring system failing to normal running. Medical wastes incineration facility usually contains waste feeding system, incinerator, flue gas purification system, slag treatment system, etc. Different techniques could be used to different systems, and then medical wastes disposal technologies present various combinations of different systems. The hardware structure and pollutant control measures of medical waste disposal facilities were listed in Figure 4.

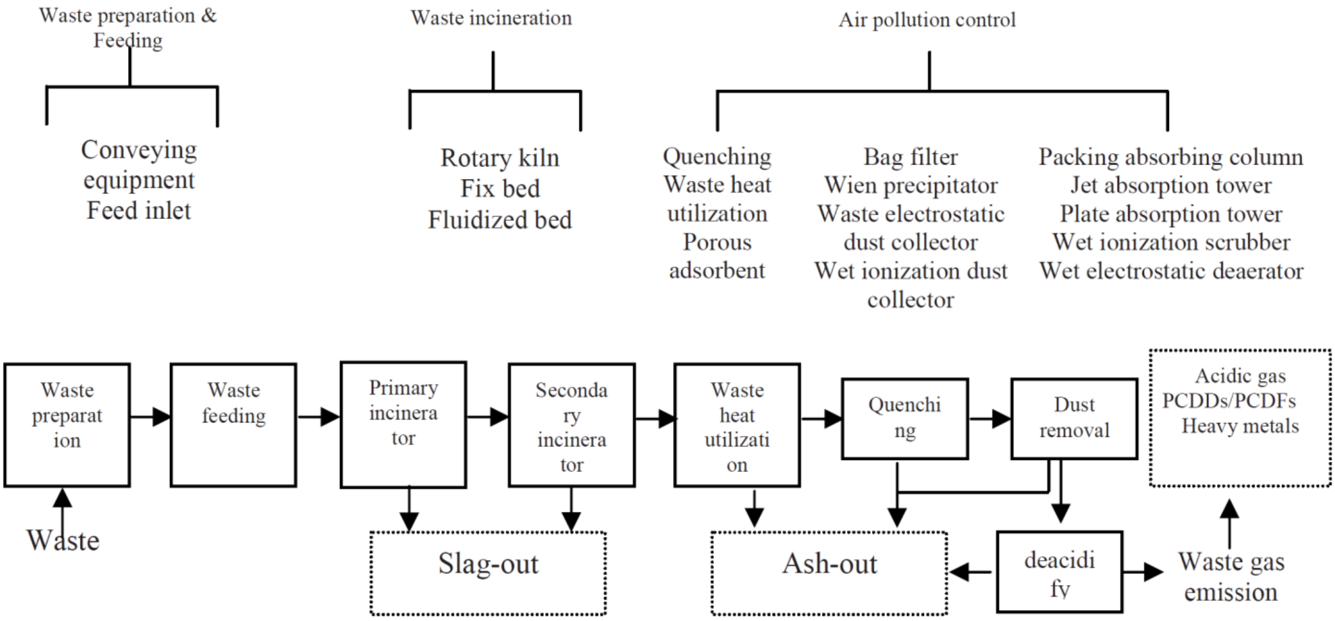


Fig. 4 The hardware structure and pollutant control measures of medical waste disposal facilities

The urgency of dioxin control of incineration system has become increasingly prominent. Hazardous waste incineration pollution control standard is under revising. It is planned to adjust dioxin release concentration from 0.5 ngTEQ/Nm3 to 0.1ngTEQ/Nm3. The exiting medical waste incineration disposal facility is facing the urgent need of retrofitting and optimizing.

Komilis et al. [52] present A study aimed to calculate the hazardous medical waste unit generation rates (HMWUGR) of 132 healthcare facilities in Greece based on data from 2009 and 2010. The hospitals were categorized into public and private and further divided into subcategories such as birth, cancer treatment, general, military, pediatric, psychiatric, and university hospitals. Results showed that there was a significant variation in HMWUGR even among hospitals of the same category. The average total HMWUGR ranged from 0.012 kg bed^{-1} d^{-1} to 0.72 kg $bed^{-1}d^{-1}$. The infectious/toxic and toxic medical wastes were found to be 10% and 50% of the total hazardous medical wastes generated by public cancer treatment and university hospitals, respectively. The study concluded that the official number of beds can be used as a predictor of total medical waste generation rates, but other parameters may also affect generation rates. Private general and birth hospitals generated more hazardous medical waste than the respective public hospitals, and the private pediatric and psychiatric hospitals had greater HMWUGR than the corresponding hospitals in the public sector.

Pai et al. [53] the Environmental Protection Administration (EPA) of Taiwan has adopted a strategy in which incineration is adopted as the primary method of treatment and landfill as a supplement for the increasing amount of waste generated from households, businesses, and industries. Medical waste is defined as hazardous waste, and strict treatment and disposal are required. The investigation of air pollutant emissions from incinerators is carried out to meet Waste Incinerator Air Pollutant Emissions Standards (WIAPES). Soft computation techniques, such as artificial neural network (ANN), are available presently and applied in the prediction of air pollutant emissions. However, they require abundant data for training. In contrast, Grey Model (GM) only requires a small quantity of data and has a better prediction performance than ANN. The air pollutant emissions can be successfully predicted by the application of control parameters. After successful prediction, it is suggested that the GM models can be employed to find out the best design or operation strategy for medical incinerator air emission control using optimization methods in future studies.

Winnefeld and Brooks [54] discuses medical waste management, covering sources, laws, and disposal methods. While many developed countries have medical waste legislation, there is often no clear guidance on what objects should be classified as infectious, leading to inefficient waste sorting and increased volume of waste treated for pathogens, usually by incineration. This unnecessary classification leads to higher costs and environmental damage. The paper concludes that educating healthcare workers and standardizing waste sorting are important for efficient waste management in healthcare facilities, and more research is needed due to the increasing production of medical waste with global economic growth. The field of medical waste disposal needs further study to meet the growing demand caused by increasing healthcare usage.

Current strategies involve sorting waste at the point-of-disposal and treating it by incineration or autoclaving, but both methods have drawbacks. To control the impact of medical waste, the most effective solution is to produce less waste. Governments can help by providing explicit, standardized definitions of infectious and non-infectious medical waste, regulating disposal to prevent illegal dumping, and incentivizing healthcare facilities to reduce waste production. Research should also be increased to develop medical products that release negligible amounts of dioxins or mercury when incinerated, particularly for use in developing nations.

Silva and Lopes [55] work on a study involved researching and analyzing the best available technologies for incinerating hospital and dangerous solid waste, proposing new measures and mitigation strategies for environmental impacts, and presenting a monitoring plan. The impacts from the installation are generally small, except for those related to gaseous emissions and energy consumption. The project is complex and multidisciplinary, requiring good communication between suppliers and technical support for interpreting the incineration process. Continuous improvement is important, and creating an environmental statement based on ISO 14000 would help demystify associated impacts and improve the installation's environmental performance.

II. CONCLUSION

In conclusion, the results obtained from this research provide valuable insights into the effectiveness of incineration as a method for reducing the volume and hazardous nature of medical waste. It is evident that incineration offers a viable solution for disposing of infectious waste and mitigating the associated health risks. However, it is crucial to consider the negative environmental impacts associated with incineration and explore alternative, more sustainable methods of medical waste disposal.

- The studies conducted on MBA (Medical Waste Incineration Fly Ash) and MFA (Medical Waste Incinerator Fly Ash) demonstrate promising prospects for integrating these waste byproducts into cement production, glass ceramics manufacturing, and vitrification techniques. These findings highlight the potential for sustainable waste management and recycling practices in the medical waste incineration process. Additionally, the investigations into safe disposal and detoxification methods, such as thermal plasma torch technology and supercritical water treatments, underscore the importance of implementing comprehensive approaches for addressing the environmental challenges posed by medical waste incinerator fly ash.

- Furthermore, the presence of PCBs in the flue gas of medical waste incinerators necessitates the implementation of measures to minimize their formation and emission. The use of inhibitors and effective air pollution control devices, including bag filters, can effectively reduce the release of PCBs and mitigate their impact on human health and the environment.
- In the case of heavy metals, the studies emphasize the importance of employing efficient methodologies such as gas filtration, self-propagating high-temperature reactions, and stabilization/solidification processes to minimize the emission and leaching of heavy metals during medical waste incineration. By adopting these approaches, the associated environmental and health hazards related to heavy metal contamination can be effectively mitigated.
- Regarding PAHs, controlling their release during medical waste incineration necessitates the implementation of appropriate waste management practices, advanced incineration technologies with effective air pollution control systems, and specific strategies such as the use of porous alumina bed material. Careful monitoring and treatment of the resulting ash, particularly with regard to heavy metals and PAHs, are essential to prevent environmental contamination and ensure safe disposal or recycling.

Overall, this research contributes to the understanding of the environmental impacts and challenges associated with medical waste incineration. The findings underscore the practices, exploring alternative incineration methods, and utilizing effective pollution control devices to minimize the environmental consequences and health risks associated with medical waste incineration.

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