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Review Article

Resource Recovery from Fly Ash Incineration of Municipal Solid Waste: Formation, Characterization, Regulations, and Treatment Technologies: A Technical Review

Furqan Ahmad[1*], **Muhammad Haris Malik**[2], **Zaryab Basharat**[3], **Muhammad Usman Amjad**[4] and **Zulqarnain Hyder**[5]
[1*,5]State Key Laboratory of Multiphase Flow in Power Engineering, School of Energy and Power Engineering, [2]Department of Fluid Machinery and Engineering, [3]MOE Key Laboratory of Thermo-Fluid Science and Engineering, [4]Research Center for Solid Waste Treatment and Recycling, Xi'an Jiaotong University, China
[1*,2,3,4]Department of Mechanical Engineering, University of Engineering and Technology Lahore (Narowal Campus), Pakistan

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Correspondence
hafizfurqanahmad538@gmail.com

ORCID
Furqan Ahmad
https://orcid.org/0009-0003-3148-0887
Muhammad Haris Malik
https://orcid.org/0009-0008-1618-4699
Zaryab Basharat
https://orcid.org/0009-0008-1914-3331
Muhammad Usman Amjad
https://orcid.org/0009-0001-3887-1173
Zulqarnain Hyder
https://orcid.org/0009-0009-5414-1566

Abstract

In addition to providing a valuable solution for waste volume reduction and energy recovery, Municipal Solid Waste Incineration (MSWI) produces fly ash (FA), a significant hazardous byproduct. This fine particulate residue, which accounts for approximately 2–5% of the input mass, is categorized as hazardous waste globally due to its high concentration of toxic heavy metals, chlorides, and persistent organic pollutants. Current disposal practices, such as stabilization and landfilling, represent a linear and unsustainable model that forfeits valuable embedded resources. This paper comprehensively examines the paradigm shift toward the resource recovery of MSWI FA in alignment with circular economy principles. It discusses the formation, physicochemical properties, and complex composition of fly ash, highlighting its variability depending on the incinerator type and waste input. A comparative analysis of international regulatory frameworks (EU, USA, China, and Japan) establishes the compliance landscape. The review critically assesses state-of-the-art treatment technologies, including separation processes (e.g., acid washing and FLUREC metal recovery), advanced stabilization/solidification methods (e.g., geopolymers and carbonation), and thermal treatments (e.g., vitrification). These pathways are evaluated for their technical effectiveness in detoxification and resource extraction, as well as their environmental impact through life-cycle assessment. The paper concludes that integrating efficient and low-impact recovery technologies is essential to transform MSWI fly ash from an environmental liability into a sustainable source of secondary materials, thereby mitigating long-term risks and advancing environmentally sustainable waste management.

I. INTRODUCTION

The most significant logistical and environmental challenges of the twenty-first century is the management of municipal solid waste (MSW) [1]. As more people move into cities and their consumption habits become more intensive, the amount of waste produced by the residential, commercial, industrial, and institutional sectors is increasing at an exponential rate. Due to their high land requirements, greenhouse gas emissions, and the potential for leachate to contaminate soil and groundwater, conventional disposal methods, particularly landfilling, are increasingly being recognized as unsustainable [2]. In response, waste-to-energy (WtE) technologies, particularly municipal solid waste incineration (MSWI), have gained prominence as a strategic solution that addresses two critical issues simultaneously: a significant reduction in waste volume and the recovery of resources in the form of heat and electricity [3].

Incineration can reduce waste volume by up to 90% and mass by 70–80% by thermally converting waste into inert ash and flue gases. The recovered energy can also replace fossil fuels, thereby promoting a more sustainable energy cycle [4].

One significant side effect of MSWI's environmental advantages is the creation of solid residues, namely fly ash (FA) and bottom ash. Bottom ash, the coarser, non-combustible material collected at the furnace bottom, is often utilized in construction, whereas fly ash poses a far greater environmental and regulatory concern [5]. The fine particulate matter carried by flue gases and captured by advanced air pollution control systems (APCS), such as scrubbers, fabric filters (baghouses), and electrostatic precipitators, is referred to as fly ash [6]. Although it constitutes only 2–5% of the total mass input of MSWI, its environmental significance is disproportionately large. This fine powder, typically less than 100 µm in diameter, acts as a primary medium for the condensation and enrichment of volatile and semi-volatile hazardous constituents [7]. When the flue gas stream cools, metals, along with chlorides, sulfates, and alkali salts, condense onto the surface of fine ash particles or form new compounds. Because persistent organic pollutants (POPs), such as dioxins and furans, may form de novo in the post-combustion zone, MSWI fly ash is often highly enriched with toxic heavy metals, soluble salts (particularly chlorides derived from plastics such as PVC), and trace levels of POPs [8].

Many countries, including the European Union, Japan, and, under certain circumstances, the United States and China, have classified MSWI fly ash as hazardous waste because of its hazardous nature. This classification mandates strict handling, treatment, and disposal protocols, typically requiring stabilization or solidification prior to landfilling in specialized hazardous waste facilities [9]. The conventional practice of “treat and dispose” represents a linear economic model that not only incurs significant costs for chemicals such as cement, energy for treatment, and landfill fees, but also results in the permanent loss of valuable resources embedded within the ash. Notably, MSWI fly ash contains considerable quantities of valuable metals; zinc and lead concentrations can reach levels significant enough to be considered a secondary ore [10]. Furthermore, its major chemical composition, dominated by CaO, SiO_2, and Al_2O_3, resembles that of many industrial raw materials used in construction and ceramics. As a result, the current disposal paradigm is increasingly regarded as both economically and environmentally inefficient, contradicting global circular economy principles that prioritize waste prevention, reuse, and resource recovery [11].

A paradigm shift in academic research and industrial practice toward the resource recovery of MSWI fly ash has been triggered by this growing discrepancy [12]. The objective is no longer merely to immobilize and contain its hazards but to actively dismantle its complex matrix in order to recover valuable components, thereby transforming a hazardous waste stream into a source of secondary materials. This approach aligns with broader sustainability goals, including resource conservation, reduction of primary mining activities, and decreased reliance on landfill space. The technical pathways for resource recovery are diverse and multifaceted, reflecting the complex physicochemical nature of the ash [13].

The viability and sustainability of any recovery pathway are not determined solely by technical feasibility. They are critically governed by a tripartite framework encompassing environmental safety, economic viability, and regulatory compliance [14]. Environmentally, any process must demonstrate the long-term stability of treated residues, ensuring that recovered materials or secondary products do not become future sources of pollution through leaching or emissions [15].

Life-cycle assessment (LCA) has become an essential tool for comparing the overall environmental impacts of different treatment and recovery pathways, including their contributions to global warming and toxicity, against conventional disposal practices. Economically, the process must balance the market value of recovered resources (e.g., metals and aggregates) with the avoided costs of hazardous waste disposal [16]. In many cases, the economic incentive for metal recovery is strengthening as ore grades decline and metal prices fluctuate. Regulatory frameworks provide the mandatory boundary conditions for these processes [17]. As highlighted in the global analysis within this report, standards for leaching limits (e.g., the EU leaching limit values, the United States Toxicity Characteristic Leaching Procedure (TCLP), and China’s GB standards) vary significantly, directly influencing which treatment technologies are permissible and how “clean” a recovered product must be to exit the waste classification and enter commercial markets [18].

This paper begins by establishing a foundational understanding of MSW, including its sources, composition, and the severe environmental impacts associated with its mismanagement. It then examines the incineration process itself, including the underlying technology, different incinerator types (moving grate, fluidized bed, and rotary kiln), and the characteristics of the resulting ashes, with a focused comparison between bottom ash and the more problematic fly ash. A significant portion of the study is dedicated to the detailed characterization of fly ash, including its formation mechanisms, physical and chemical properties, heavy metal content, and mineralogical composition, as revealed by techniques such as X-ray diffraction (XRD). The report further investigates the influential role that fly ash plays in incineration performance, affecting combustion efficiency, heat transfer, and pollutant control.

The analysis then expands to a global perspective by presenting data on fly ash generation trends worldwide and conducting a comparative examination of regulatory frameworks in different regions. This perspective highlights the diverse policy approaches and technical standards that shape local waste management practices. Finally, the core of the report critically reviews the current state-of-the-art treatment technologies aimed at resource recovery. This includes an in-depth analysis of separation processes (such as washing and the FLUREC process), stabilization or solidification methods (with a focus on reducing cement usage and exploring alternatives such as carbonation), and thermal treatment processes. These technologies are evaluated not only in terms of technical effectiveness but also through environmental impact assessments, illustrating the trade-offs and advancements associated with sustainable management practices. Transforming the perception of MSWI fly ash from hazardous waste to a valuable resource is both necessary and beneficial. It is essential for mitigating long-term environmental risks and reducing landfill dependence, while also presenting an opportunity to contribute to resource security and the development of a circular economy. This report synthesizes current scientific knowledge, technological advancements, and regulatory frameworks to provide a comprehensive overview of this critical field. It aims to inform researchers, policymakers, and industry practitioners about the complexities, challenges, and promising pathways toward the sustainable and resource-efficient management of MSWI fly ash.

II. MUNICIPAL SOLID WASTE

Municipal solid waste (MSW) refers to the common waste generated by households, commercial establishments, industries, and healthcare institutions. This broad category includes organic matter, plastics, metals, glass, paper, and other discarded materials that are collected and managed by municipal services. Due to variations in population density, consumer behavior, and economic development, the composition and quantity of MSW vary significantly across regions. Effective waste treatment and sustainable disposal methods are essential, as improper MSW management can lead to severe environmental problems, such as air pollution, groundwater contamination, and the proliferation of disease vectors.

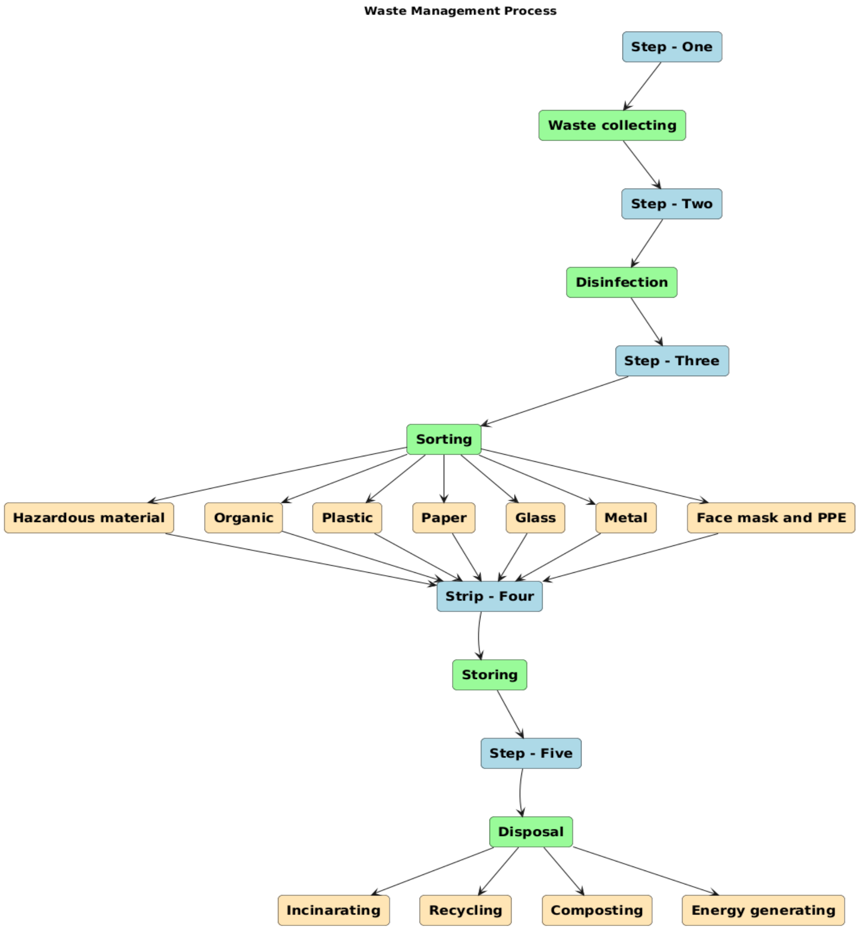


Fig.1 Pathway of MSW Handling

A. Composition of MSW

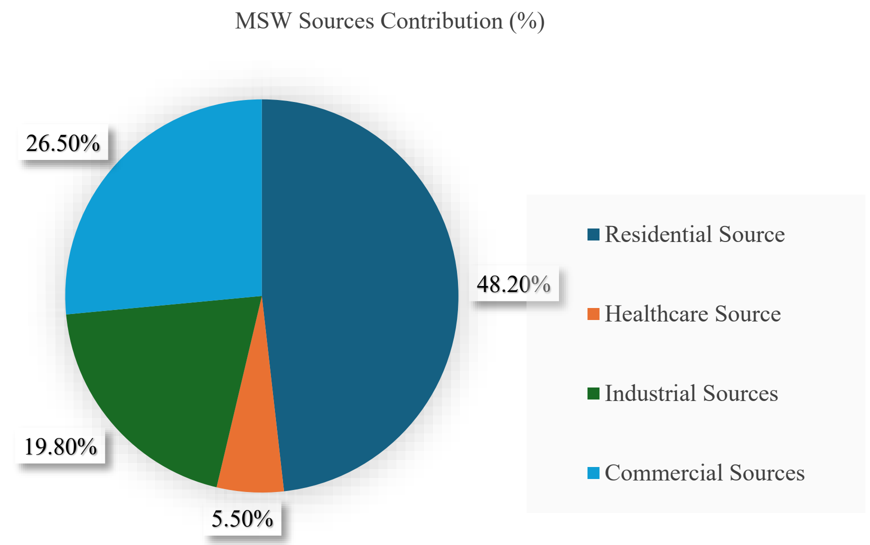


Fig.2 MSW Sources Contribution [19], [20]

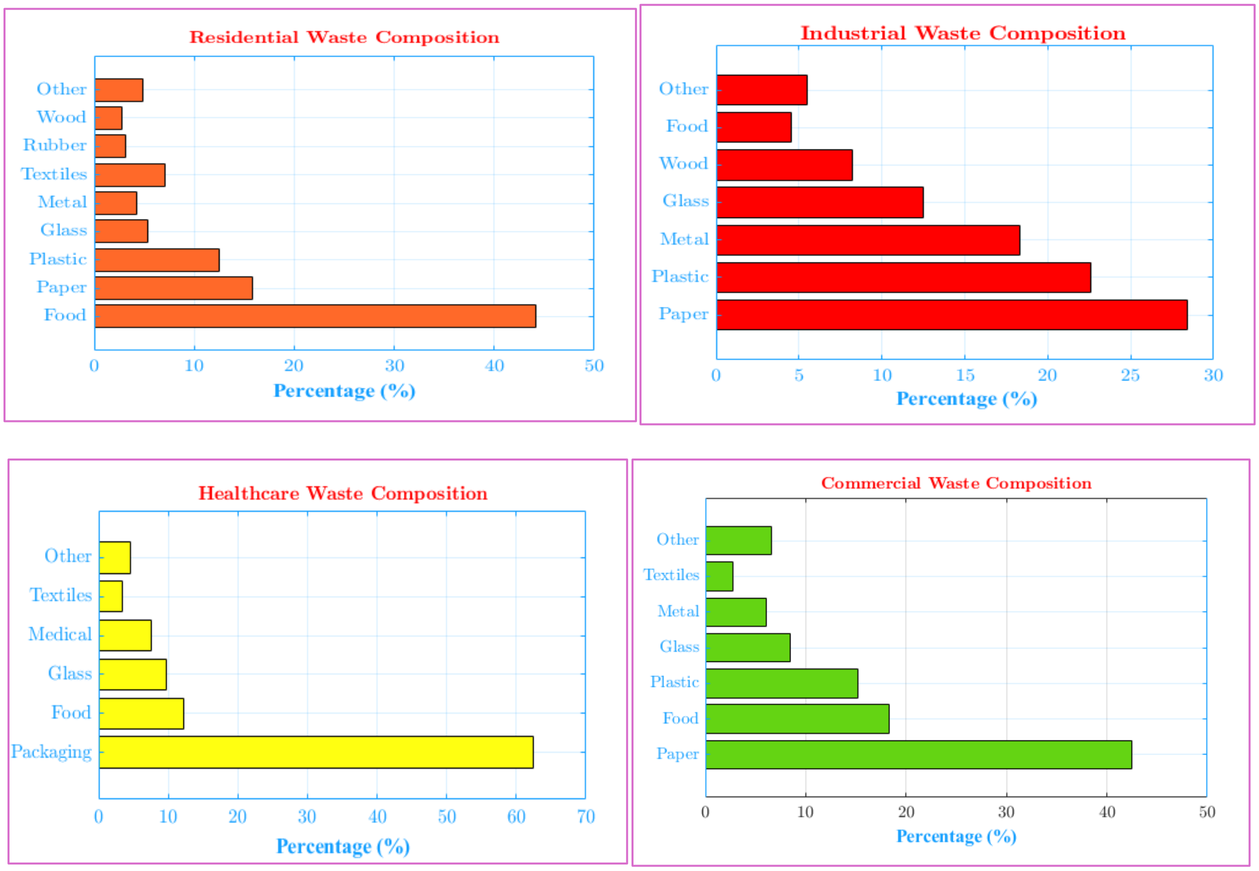


Fig.3 (a) Residential Waste Composition [22], (b) Industrial Waste Composition [23],
(c) Healthcare Waste Management [24], (d) Commercial Waste Composition [25]

Figure 2 presents a comprehensive breakdown of MSW sources and their material composition. The proportional contributions of different waste generation sources are shown, with residential activities accounting for nearly half of the total MSW (48.20%) [19], followed by commercial (26.50%) [20], industrial (19.80%), and healthcare sectors (5.50%). This distribution underscores the dominant role of household consumption in urban waste streams while highlighting the significant combined contribution of commercial and industrial activities (46.30%) [20]. Subsequent panels detail the material composition within each waste source, as shown in Fig. 2. Residential waste (a) is characterized by high organic content (44.2% food waste), accompanied by substantial paper (15.8%) and plastic (12.5%) components, reflecting typical household consumption patterns. Industrial waste (b) shows significant proportions of paper (28.4%), plastic (22.6%), and metal (18.3%), representing manufacturing byproducts and packaging materials. Healthcare waste (c) is distinguished by exceptionally high packaging content (62.5%), primarily paper and plastic materials from medical supplies and administrative operations. Commercial waste (d) exhibits a contrasting profile dominated by paper products (42.5%), with notable contributions from food waste (18.3%) and plastics (15.2%), indicative of packaging-intensive retail and office environments. These material-specific profiles demonstrate the necessity for sector-specific waste management strategies and highlight opportunities for source-separated recycling initiatives [21].

B. Environment Impact of Improper MSW Management

Improper management of municipal solid waste poses serious environmental challenges that directly threaten air, soil, and water quality [26]. Leachate, a contaminated liquid produced by the decomposition of organic waste, may seep into the ground and contaminate soil and groundwater with heavy metals, pathogens, and hazardous chemicals when waste is disposed of in open spaces or poorly managed landfills. This contamination can persist for decades and adversely affect agricultural productivity and drinking water safety [27]. Furthermore, the uncontrolled decomposition of organic waste releases methane, a potent greenhouse gas that contributes significantly to climate change. Many developing regions lack proper landfill gas recovery systems, allowing methane and other toxic gases, such as ammonia, sulphur compounds, and volatile organic compounds, to escape into the atmosphere [28].

The relative severity of environmental impacts caused by improper MSW management is illustrated in **Fig. 4**, which categorizes six major impact types. Air pollution emerges as the most severe impact at 90%, primarily driven by open burning practices that release particulate matter (PM2.5), dioxins, and volatile organic compounds, often exceeding World Health Organization (WHO) air quality guidelines. Water pollution follows closely at 85%, reflecting widespread groundwater contamination from landfill leachate containing heavy metals, nitrates, and organic pollutants that percolate into aquifers and surface water bodies. Soil contamination (80%) and greenhouse gas emissions (76%) represent substantial secondary impacts. Soil systems accumulate persistent heavy metals and organic pollutants, disrupting soil ecology and agricultural productivity, while methane emissions from anaerobic decomposition in landfills contribute significantly to climate forcing. Health risks (75%) arise through direct exposure pathways, including respiratory diseases from airborne particulates, waterborne illnesses from contaminated water sources, and vector-borne diseases associated with waste accumulation sites. Ecosystem damage (65%), although slightly lower in relative severity, reflects broader ecological consequences, including habitat degradation, biodiversity loss, and disruption of nutrient cycles in terrestrial and aquatic systems. This hierarchy of impacts underscores the interconnected nature of waste-related environmental degradation and highlights the urgent need for integrated waste management strategies to mitigate these cascading effects.

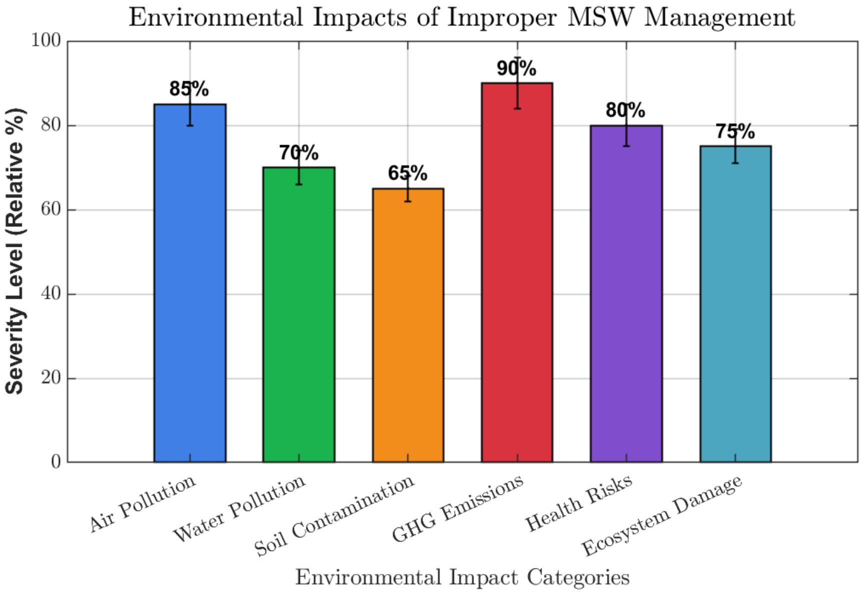


Fig.4 Environment Impact of Improper MSW Management [29], [30], [31]

III. INCINERATION

Incineration is a thermal waste treatment process in which municipal solid waste (MSW) is burned at high temperatures to reduce its volume and convert it into stable end products such as ash, flue gases, and heat. It typically operates at temperatures ranging from 850°C to 1100°C, allowing complete oxidation of organic materials present in the waste [32]. The basic principle of incineration involves the controlled combustion of waste in the presence of sufficient oxygen, which breaks down complex organic compounds into simpler gases like carbon dioxide (CO_2) and water vapor (H_2O). During this process, the chemical energy stored in the waste is released as heat, which can be recovered and used for electricity generation or district heating through Waste-to-Energy (WtE) systems [33]. A standard incineration system consists of several phases, including waste drying, volatilization, combustion, and burnout. The waste first loses moisture through drying, followed by the release of volatile gases, which ignite and support further combustion [34]. The remaining solid material undergoes oxidation until only inert ash remains. Modern incineration plants are equipped with advanced flue gas cleaning systems to remove pollutants such as particulate matter, dioxins, acidic gases, and heavy metals, ensuring compliance with environmental standards. Overall, incineration serves as an effective waste management strategy by significantly reducing waste volume while enabling energy recovery [35].

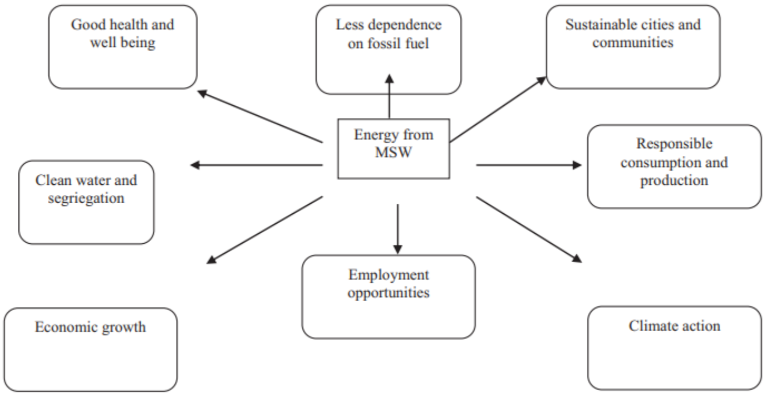


Fig.5 Chart of WtF Process [33]

The incineration process is separated into three main parts: incineration, energy recovery and air pollution control. Figure 6 shows a schematic diagram depicting the common MSW incineration process. The MSW is fed into the furnace continually for incineration. Based on the Best Practical Means for the combustion of wastes, the combustion is enhanced by following the three T's guideline high Temperature increases burnout, increased Turbulence exposes more waste surface and increases burnout, and a longer residence Time for the flue gas (>2 seconds) and the MSW increases burnout the temperature for incineration should be at least 850 °C with a residence time of more than two seconds. During the process, the air supply must be sufficient to ensure complete combustion of waste and to prevent the formation of dioxins and carbon monoxide [36].

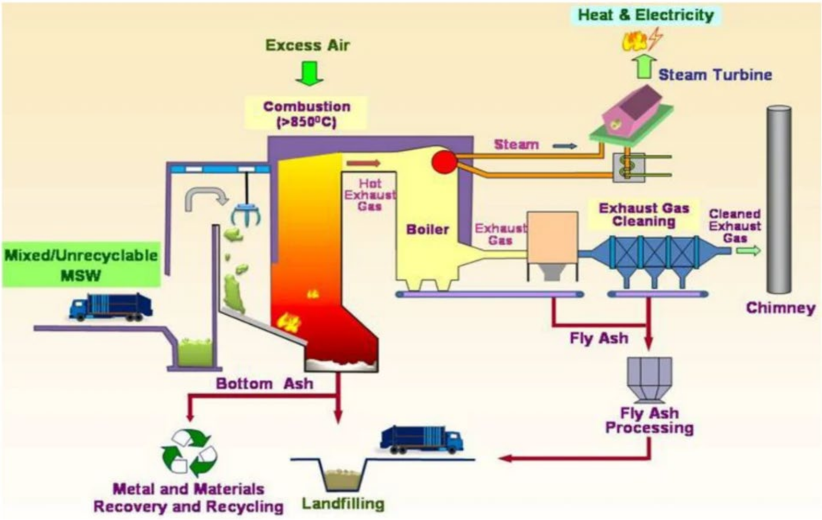


Fig.6 Schematic Diagram of the MSW Incineration Process [36]

For energy recovery, the heat generated from waste is used to produce steam in the boiler. Then the steam drives the turbine to generate electricity. The excess heat generated can also be used for other purposes, e.g., heating for swimming pools. Air pollution is a major problem for incineration. In modern incinerators, an advanced pollution control system is designed to minimize the pollution and ensure compliance with environmental standards [37]. A dry/wet scrubber is used to spray fine atomized slurry or lime powder into the hot exhaust gas to neutralize the acidic gases such as sulfur oxides and hydrogen chloride. An activated carbon column or injected activated carbon spray is used to adsorb the heavy metals and organic pollutants such as PCB and VOC in the exhaust gas. A selective non-catalytic reduction system is used to remove nitrogen oxides by adding urea or ammonia for reaction to nitrogen, carbon dioxide and water. The bag filter system acts to filter and remove the fine particulates and dust particles [38]. Incineration of municipal solid waste (MSW) results in three primary end products:

1. Bottom ash
2. Fly ash
3. Flue gases

These residues differ in their composition, environmental risk, and potential for reuse. Understanding their characteristics is essential for designing safe disposal strategies and resource recovery processes.

TABLE I COMPARISON BETWEEN BOTTOM ASH AND FLY ASH IN TERMS OF TOXICITY AND UTILIZATION

Parameter	Bottom Ash	Fly Ash	Ref.
Proportion of Total Ash	80–90%	10–20%	[43]
Particle Size	Coarse (gravel-like)	Fine powder (<1 mm)	[43]
Toxicity Level	Lower; fewer heavy metals	Higher; concentrated heavy metals and dioxins	[26]
Typical Classification	Non-hazardous (in most cases)	Often hazardous	[28]
Chemical Composition	Silicates, metal oxides, glass, ceramics	Heavy metals, chlorides, sulfates, toxic organics	[21]
Environmental Risk	Moderate	High (requires strict handling)	[44]
Reuse Potential	High (construction, road base, metal recovery)	Limited; requires stabilization before reuse	[33]
Disposal Requirement	Regular engineered landfill	Hazardous waste landfill or stabilized form	[45]
Metal Content	Moderate to high (recoverable metals)	High, but recovery more difficult due to particle size	[46]

IV. FLY ASH

When MSW is incinerated, a fine and powdery residue known as fly ash is produced. Carried upward with the flue gases, it is subsequently collected by air pollution control devices such as fabric filters, scrubbers, and electrostatic precipitators. Although fly ash typically accounts for only 2–5% of the total MSW input, it contains highly concentrated pollutants because the smaller particles tend to accumulate heavy metals, salts, and organic contaminants during combustion.

A. Formation of Fly Ash

When MSW is burned in incinerators, fly ash is produced as a fine particulate byproduct. During the high-temperature combustion process, organic compounds are largely combusted, while inorganic components such as metals, minerals, salts, and unburned carbon volatilize or fragment into extremely small particles. Due to the high combustion air velocity and turbulent flow within the furnace, these particles are subsequently transported upward with the exhaust gases. As the flue gases cool, volatile species, including heavy metals (lead, cadmium, zinc, and mercury), alkali salts (KCl and NaCl), sulphates, and chlorides, condense onto the surface of these fine particles, enriching the fly ash with hazardous and highly reactive substances. The formation of fly ash is strongly influenced by several factors, including the type of waste being incinerated, the combustion temperature (typically between 850 and 1100 °C), the presence of plastics and chlorine-containing materials, and the design of the incinerator. Moving grate systems generally produce larger ash particles with a wider size distribution, whereas fluidized bed incinerators tend to generate smaller and more uniformly distributed particles due to their higher turbulence. After passing through the boil. er sections, the fly ash must be captured by air pollution control systems such as cyclones, baghouse filters, and electrostatic precipitators. Because of its fine particle size and elevated concentrations of toxic heavy metals, fly ash is classified as hazardous waste in many countries, requiring specialized management, stabilization, or resource recovery processes.

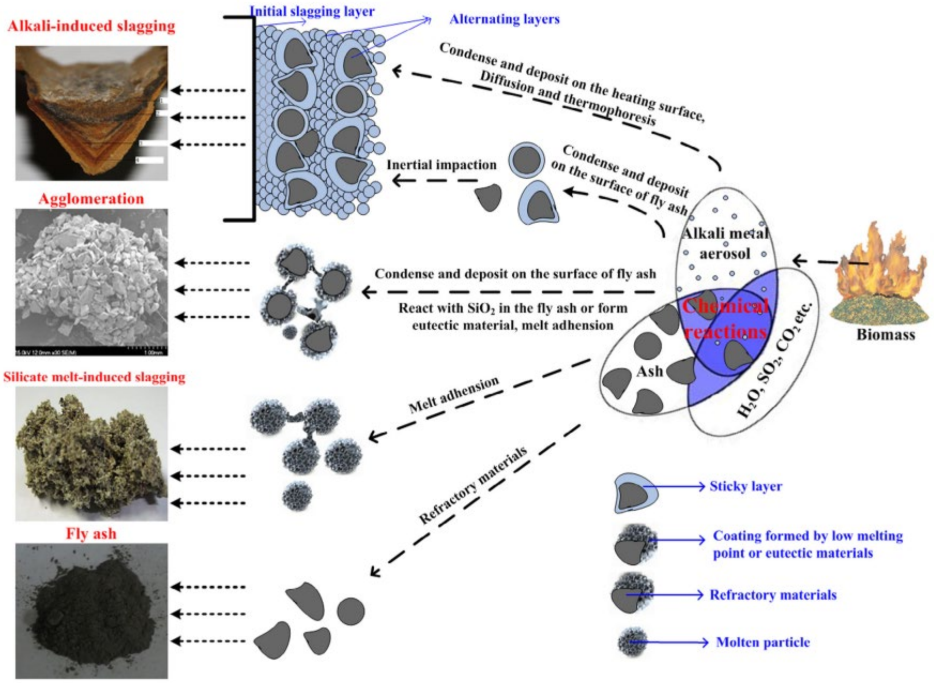


Fig.7 Formation of ASH [47]

B. X-ray Diffraction (XRD) Analysis

Figure 8 provides the characteristic "fingerprint" of crystalline mineral phases present in MSWI fly ash. The diffraction peaks, which appear as sharp increases in intensity at specific 2θ angles, correspond to distinct crystal lattice structures of minerals formed during high-temperature incineration. The most prominent peaks are labeled with letter codes: Q (quartz, SiO_2) and C (calcite, $CaCO_3$) show the strongest intensities, indicating that these are the dominant crystalline phases. Other identifiable peaks correspond to salts such as sylvite (KCl) and halite (NaCl), along with minor phases including iron oxide (hematite), calcium hydroxide (portlandite), and calcium oxide (lime). The broad, low-intensity region around 25–35° 2θ suggests the presence of amorphous (non-crystalline) glassy material that does not produce sharp diffraction peaks.

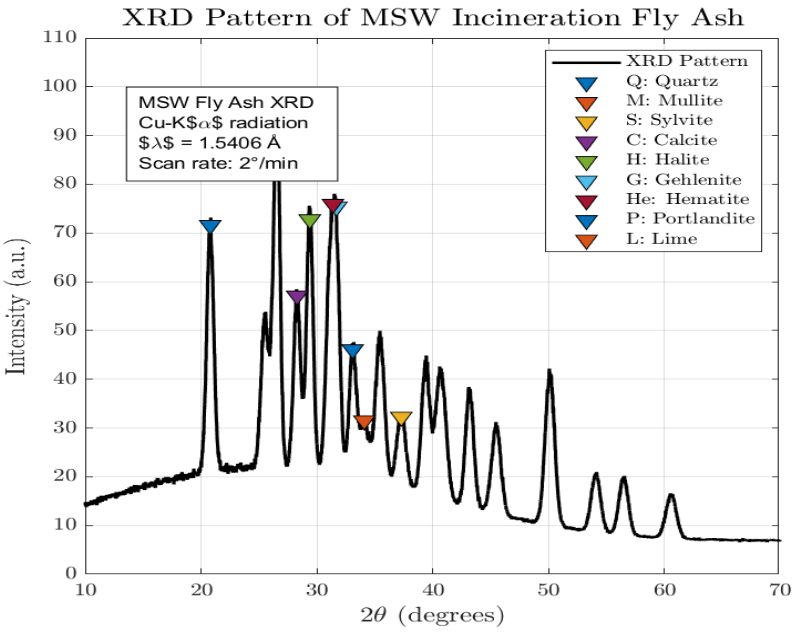


Fig.8 XRD Pattern of MSW Incineration Fly Ash

Figure 9 visualizes the decomposition of the composite XRD pattern into its individual mineral contributions through computational analysis. Each colored curve represents the calculated diffraction profile of a specific mineral phase, with their sum (the black "Total Pattern" curve) reconstructing the measured pattern. The graph shows that quartz (blue) and calcite (orange) constitute the primary crystalline components, while salt minerals such as halite (green) and sylvite (purple) contribute additional characteristic peaks. The gray dashed curve labeled "Amorphous" represents the non-crystalline fraction, which lacks well-defined diffraction peaks but contributes to the overall baseline of the pattern. This decomposition enables quantitative phase analysis, demonstrating that although the crystalline minerals produce sharp diffraction peaks, a significant portion of the fly ash exists in amorphous form, influencing its chemical reactivity and environmental behavior.

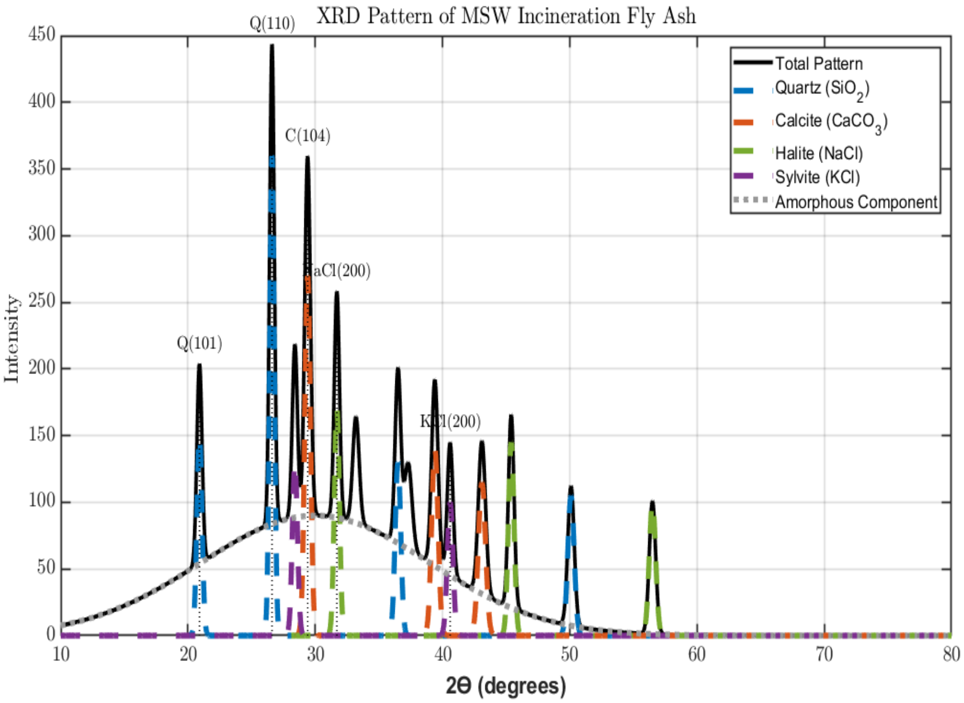
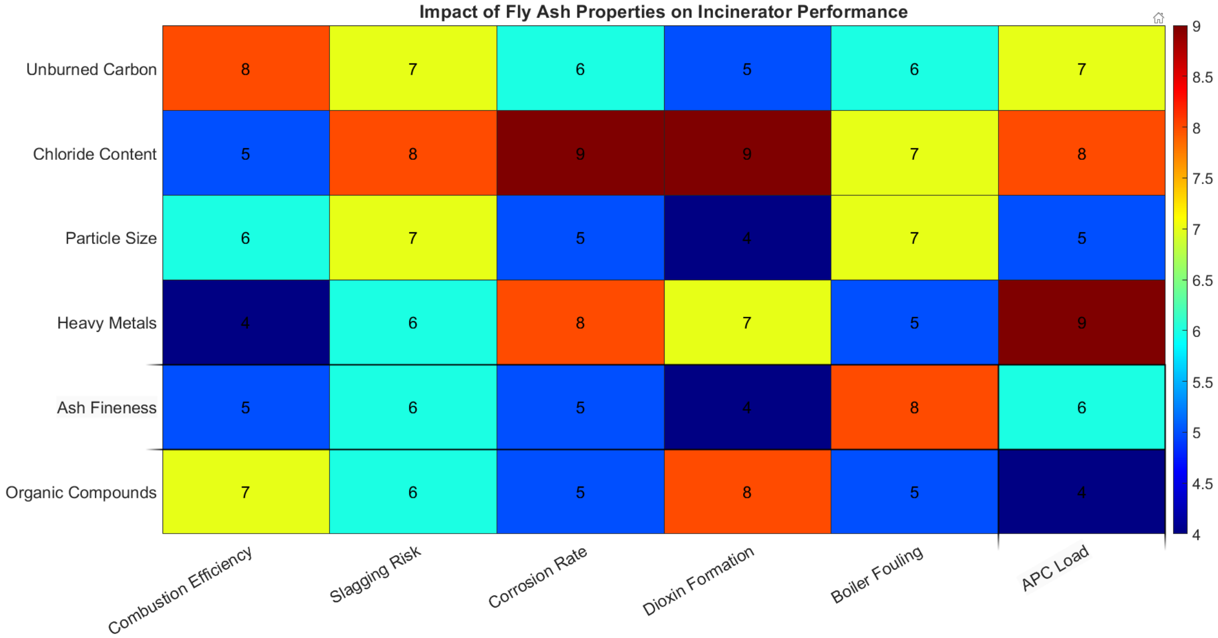


Fig.9 Phase Decomposition of XRD Pattern

C. Fly Ash Effect on Incineration

The overall effectiveness, efficiency, and environmental impact of the municipal solid waste (MSW) incineration process are significantly influenced by fly ash. Despite being a by-product, the physical and chemical properties of fly ash directly affect pollutant formation, heat transfer, combustion behavior, and gas-cleaning performance. Understanding these effects is essential for optimizing incinerator operation and ensuring safe waste disposal. One major impact of fly ash is its ability to carry unburned carbon or partially combusted particles. A high carbon content in fly ash indicates incomplete combustion inside the furnace, which reduces thermal efficiency and increases fuel consumption. When unburned carbon remains in the flue gas stream, it can also interfere with air pollution control devices by adsorbing volatile organic compounds (VOCs), dioxins, and heavy metals, potentially resulting in higher emissions if not properly managed. The mineral composition of fly ash also influences the temperature profile and slagging behavior within the incinerator. Fly ash with high silica, alumina, or calcium oxide content can melt and form sticky deposits on heat-exchange surfaces. These deposits increase fouling, reduce heat-transfer performance, and may necessitate frequent shutdowns or cleaning. Additionally, the high chloride content of fly ash accelerates the corrosion of metallic components, particularly in the boiler and superheater sections. The performance of air pollution control systems (APCs) is further affected by fly ash characteristics. Fine particles with large surface areas can enhance the reaction efficiency of sorbents such as lime or sodium bicarbonate, thereby improving the removal of acidic gases such as SO_2, HCl, and HF. However, excessive loading of bag filters with fine ash can cause pressure drops and reduce filtration efficiency. Fly ash may also contain hazardous heavy metals (e.g., Pb, Zn, Cd, and Cr), increasing the risk of secondary pollution if the APC system is not designed for effective capture and stabilization. Furthermore, the presence of specific metal catalysts (such as copper, iron, or zinc compounds) in fly ash promotes the formation and reformation of dioxins and furans in the post-combustion zone, typically within the temperature range of 200–400 °C. Consequently, the composition of fly ash can indirectly influence the release of highly toxic persistent organic pollutants (POPs). Overall, fly ash impacts the incineration process by affecting combustion efficiency, heat transfer, equipment performance, corrosion rates, pollutant generation, and emission control. Proper fly ash management—through optimized furnace operation, enhanced APC design, and safe disposal or recycling—is essential for ensuring the environmental sustainability of MSW incineration plants.

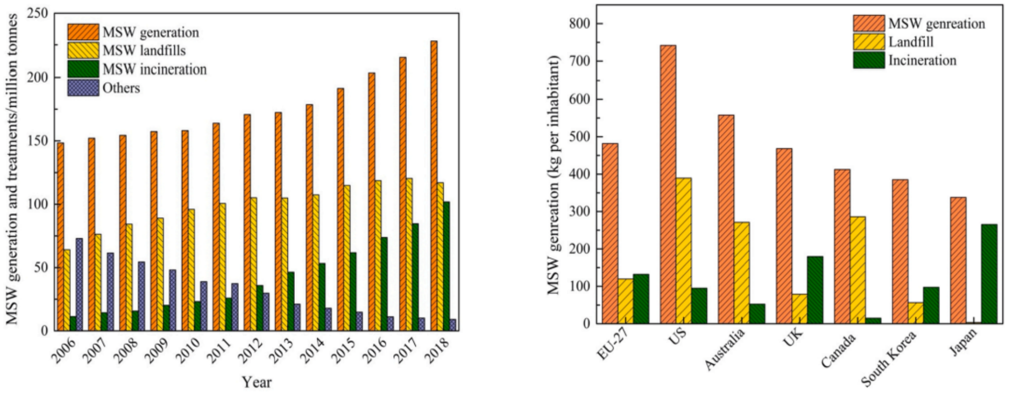


	Combustion Efficiency	Slagging Risk	Corrosion Rate	Dioxin Formation	Boiler Fouling	APC Load
Unburned Carbon	8	7	6	5	6	7
Chloride Content	5	8	9	9	7	8
Particle Size	6	7	5	4	7	5
Heavy Metals	4	6	8	7	5	9
Ash Fineness	5	6	5	4	8	6
Organic Compounds	7	6	5	8	5	4

Fig.10 Impact of Fly Ash Properties on Incinerator Performance

V. GLOBAL MSWI FLY ASH GENERATION

The expansion of municipal solid waste incineration (MSWI) worldwide has significantly increased the generation of MSWI fly ash (FA), making it a global environmental and resource management challenge. According to recent reviews, global municipal solid waste generation is approximately 2.01 billion tons per year, with expectations to rise to 3.4 billion tons by 2050 under business-as-usual scenarios [48]. Figure 11(a) shows the trend in the amounts of MSW generation, sanitary landfill, and incineration treatment in China. It can be observed that the proportion of MSWI increased along with increasing MSW generation. From 2006 to 2018, the amount of MSW treated by incineration rapidly increased from 11.4 to 101.8 million tons, representing an increase of nearly ninefold [49]. The MSW generation and treatment approaches in different countries or regions are shown in Figure 11(b). The European Union (EU) generated 482 kg of MSW per capita in 2017; the data indicate higher levels of MSW generation in both Australia (558 kg per capita) and the US (742 kg per capita). Japan reported the highest use of incineration (78.5%) to treat MSW, followed by the UK (38.4%) and the EU (27.4%). As incineration replaces or supplements landfilling in many regions, notably in parts of Asia, Europe, and North America, the by-product FA output also rises correspondingly [50].



(a) The trend of MSW generation, landfill treatment, and incineration treatment amount in China

(b) MSW generation, landfill treatment, and incineration treatment amount in some countries in 2015–2017

Fig.11 (a) MSW generation in China (b) MSW Generation in Different Countries from 2015-2017

At the national scale, some of the largest contributors to global MSWI FA appear in regions with high urbanization rates and substantial waste-to-energy (WtE) infrastructure. For example, in China, where incineration has become a principal MSW disposal route, recent data indicate that MSWI-FA production has grown markedly: one study reports that by 2022, China's MSWI-FA yield reached approximately 7.80 million tons. Other sources suggest that by 2020, China's fly ash output reached around 7.3 million tons, based on about a 5% mass fraction of the original incinerated waste. This rapid rise reflects both the growth in MSW generation and the increasing share of MSW treated via incineration rather than landfilling [51].

VI. TREATMENT OF MSWI FLY ASH

Municipal solid waste incineration fly ash (MSWI FA) contains numerous heavy metals, chlorides, sulphates, and dioxins. As a result, its disposal has become challenging, as proper management is required to protect the environment from the serious ecological risks posed by these compounds. This situation necessitates the implementation of stringent regulations and continuous monitoring to ensure compliance and to reduce pollution caused by improper MSWI FA disposal. Consequently, due to the presence of hazardous substances, fly ash has been classified as hazardous waste. Prior to recycling or landfill disposal, appropriate treatment and preparation of fly ash are required. At the industrial level, commonly used final-stage treatment methods include separation processes, solidification or stabilization techniques, and thermal treatment processes.

A. Separation Treatment

The most common separation methods are washing processes that enable the reduction of chlorides, soluble salts, and heavy metals in fly ash. During washing, soluble substances that are loosely adhered to the surface are dissolved and subsequently removed. Although this approach is considered environmentally favorable, heavy metals must still be extracted and recovered using technologies such as acid extraction, alkaline extraction, or biological extraction [83]. Chelating agents, such as EDTA/gluconate mixtures, can be used in the washing process, facilitating the dissolution of Cd, Cu, and Zn more effectively than water alone [84]. More specifically, a method known as the FLUREC process has been developed to recover Zn, Pb, Cd, and Cu from fly ash. The FLUREC technique, which stands for *fly ash recycling*, was developed by AIK Technik AG in Switzerland to treat and valorize fly ash by recovering valuable heavy metals, particularly zinc (Zn) [85]. The process involves several steps, including acid washing of the ash (FLUWA), heavy metal separation, and high-purity zinc recovery. Initially, the ash is treated with acid to extract the metals. Subsequently, zinc is recovered as a pure metal through separation processes, while other metals are appropriately treated. This process not only reduces the toxicity of fly ash but also enables the recovery and utilization of valuable metals [86]. In this process, acidic wastewater generated from the wet cleaning of combustion gases in solid waste incinerators is used as the washing agent. Studies indicate that the effectiveness of the removal process depends on factors such as oxidation–reduction potential (related to the concentration of hydrogen peroxide), pH, and the liquid–solid ratio. Consequently, the reduction in metal content is attributed to the combined effects of redox reactions and the formation of metal chloride complexes [87].

Figure 12 illustrates the relative effectiveness of various separation treatment methods for recovering zinc from MSWI fly ash. The presented techniques include water washing, acid leaching, the FLUWA/FLUREC process, and bioleaching. Based on the depicted performance hierarchy, the FLUWA/FLUREC process appears to be the most effective treatment, achieving the highest zinc recovery. Acid leaching demonstrates moderate recovery performance, while bioleaching shows a lower but still significant recovery yield. Water washing, as indicated, results in the lowest recovery efficiency among the compared methods, suggesting that it is less suitable for substantial zinc extraction from this waste stream. The visualization effectively highlights the technological differences in recovery potential, with hydrometallurgical and specialized chemical processes outperforming biological and simple aqueous treatments.

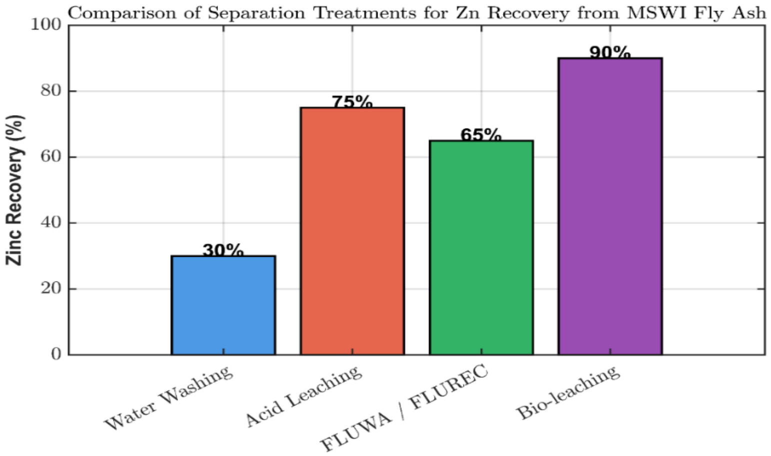


Fig.12 Comparison of Separation Treatments for Zn Recovery [88]

Figure13 presents the relationship between leaching time and the extraction efficiency of three metals—zinc (Zn), lead (Pb), and copper (Cu)—from MSWI fly ash using a hydrometallurgical process. All three metals exhibit a sharp increase in recovery during the initial leaching period, indicating rapid dissolution kinetics at the onset. As time progresses, the curves for each metal begin to plateau, signifying a transition to a diffusion-controlled regime in which the rate of metal extraction slows considerably. Zinc consistently shows the highest overall recovery across the entire time range, followed by lead and then copper, reflecting their relative solubilities and mobilities under the specified leaching conditions. The asymptotic trends suggest that beyond a certain leaching duration, extending the process time yields diminishing returns in metal extraction efficiency.

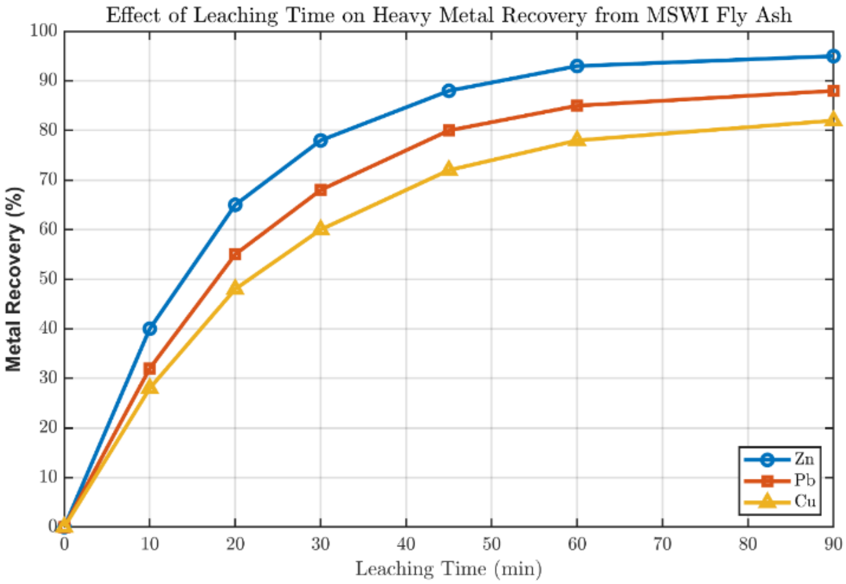


Fig.13 Impact of Leaching on Heavy Metal Recovery [89]

Figure 14 illustrates the kinetic profiles of heavy metal recovery from MSWI fly ash as a function of leaching duration. The extraction efficiency for all three metals—zinc, lead, and copper—increases rapidly at the beginning, indicating a fast, surface-reaction-dominated dissolution phase. Over time, the recovery rates for each metal gradually decelerate and approach a plateau, reflecting a shift to a slower, diffusion-limited regime in which the leaching agent must penetrate deeper into the ash matrix or through product layers. Among the metals, zinc exhibits the highest ultimate recovery, followed by lead and then copper, highlighting differences in their chemical availability and solubility under the applied leaching conditions. The asymptotic behavior of the curves suggests an optimal leaching window beyond which additional time results in minimal incremental metal extraction.

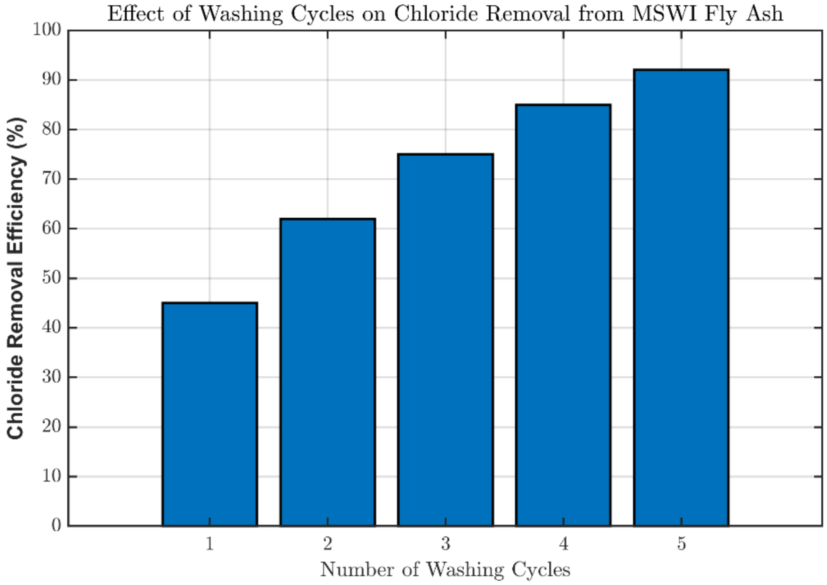


Fig.14 Effect of Washing Cycles on Chloride Removal [90]

Figure 15 illustrates the significant influence of leaching-solution pH on the removal efficiency of metals (zinc, lead, and cadmium) from MSWI fly ash. The curves for each metal exhibit distinct pH-dependent solubility profiles, with removal efficiency generally increasing as acidity increases. However, each metal demonstrates an optimal pH range, reflecting its specific chemical speciation and stability under different acidic conditions. Zinc and lead show more pronounced increases in removal within relatively narrow pH intervals, whereas cadmium appears to be efficiently removed across a broader acidic range. Overall, the results indicate that effective extraction of specific target metals from the complex fly ash matrix requires precise control of the leaching pH.

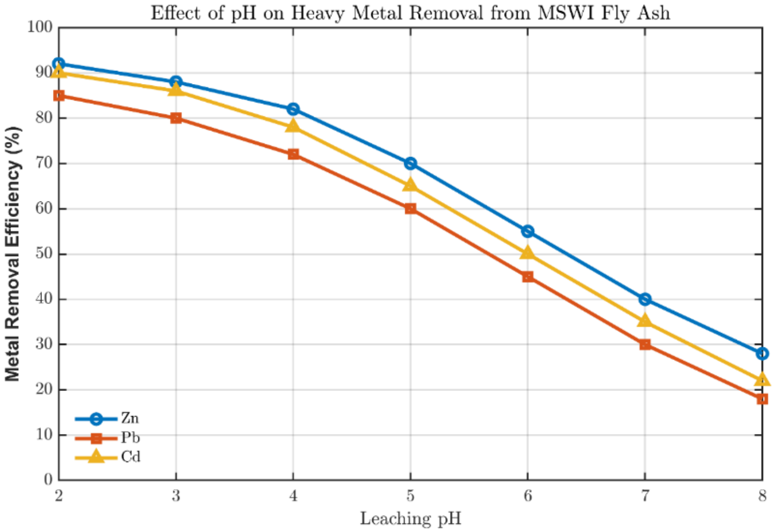


Fig.15 Effect of pH on Heavy Metal Removal [91]

B. Thermal Treatment

Different thermal techniques can be employed to remove organic pollutants such as polychlorinated dibenzo-p-dioxins (PCDD) and polychlorinated dibenzofurans (PCDF) from MSWI fly ash (FA). High-temperature processes (700–1600 °C), including sintering, melting, and vitrification, can destroy PCDD/F and immobilize certain heavy metals; however, these processes require substantial energy input. In contrast, pyrolysis and hydrothermal treatments are relatively low-temperature processes (200–374 °C) that can degrade PCDD/F, although they often require additives and additional processing steps to effectively stabilize pollutants [92]. Recent thermal purification approaches for fly ash include thermal plasma technology, hydrothermal treatment, and vitrification.

The objective of fly ash vitrification is to immobilize hazardous substances by encapsulating them within a stable glass matrix, thereby preventing leaching. Two main types of vitrification are commonly used: direct vitrification and vitrification with fluxing agents such as silica sand or crushed glass. The major limitations of direct vitrification include high energy consumption and the potential for secondary contamination due to heavy metal volatilization. During the vitrification process, most low-boiling-point heavy metal salts are incorporated into the glassy slag and effectively stabilized to reduce leaching, while a small fraction volatilizes into the combustion gases. The chemical composition of fly ash, particularly the concentrations of chlorine (Cl) and sulfur (S), strongly influences the heating behavior. Secondary fly ash may be generated when metallic components, especially lead, volatilize due to the presence of chlorides and are subsequently captured by the furnace flue-gas dedusting system. Heavy metals contained in this secondary fly ash can later be recovered through water or acid leaching processes [54].

In the thermal plasma process, fly ash is melted using a high-temperature electric arc that can exceed 1400 °C. The intense radiation and heat produced can raise the material to fusion temperatures, transforming pollutants into a stable glassy matrix that significantly reduces their mobility and toxicity. As a result, this process can reduce the volume of MSWI fly ash by approximately 49%–70%. Moreover, by controlling the plasma using electrical power, ultra-high temperatures between 3000 °C and 5000 °C can be achieved. The energy generated by thermal plasma can be regulated by adjusting the electrical current and surrounding operating conditions. During this process, heavy metals with low boiling points volatilize and enter the flue-gas treatment system, whereas high-boiling-point heavy metals generally remain within the slag. Studies have shown that plasma treatment of MSWI fly ash can reduce heavy metal leaching to levels below regulatory limits. However, the requirement for specialized infrastructure and the high operational costs remain significant drawbacks [54]. Hydrothermal processing is another promising approach for stabilizing MSWI fly ash while reducing environmental hazards and enabling potential recycling. These treatments typically operate at temperatures of approximately 200 °C under alkaline aqueous conditions, promoting the formation of zeolite-like structures from the silica- and alumina-rich components of the ash.

Figure 16 illustrates the effect of heat-treatment temperature on the leaching potential of lead and zinc from MSWI fly ash. As the temperature increases, the leaching behavior of both metals exhibits distinct non-linear trends, reflecting complex physicochemical transformations within the ash matrix. Initially, lower-temperature treatments may increase metal mobility due to the decomposition of organic matter and phase transformations. However, at higher temperatures, a substantial reduction in leaching occurs, primarily due to the encapsulation of metals within newly formed silicate or glassy phases and the volatilization of more volatile species. The behaviors of lead and zinc diverge across the temperature range, indicating differences in their thermal stability, volatilization thresholds, and tendencies to incorporate into stable mineral structures. The results suggest that an optimal thermal-treatment window exists for stabilizing these heavy metals, beyond which their environmental mobility is significantly reduced.

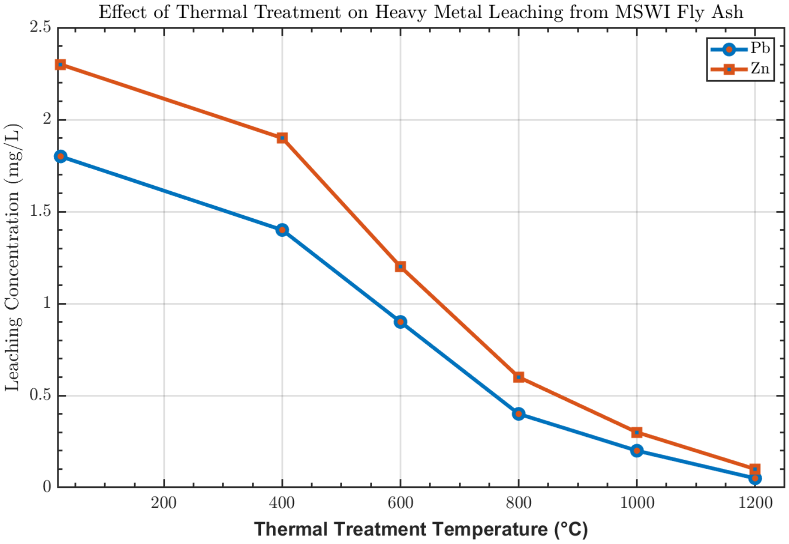


Fig.16 Effect of Thermal Treatment on Heavy Metal Leaching [93]

Figure 17 illustrates the influence of increasing heating temperature on the phase composition of MSWI fly ash. As the temperature rises, the proportion of amorphous, or glassy, phases increase significantly, while the content of crystalline phases decreases correspondingly. This transition reflects a fundamental solid-state transformation in which originally distinct crystalline mineral components begin to decompose, melt, and subsequently vitrify upon cooling, forming a homogenized, non-crystalline glass matrix. This behavior indicates sintering and partial melting phenomena occurring within the ash, resulting in microstructural densification and encapsulation of constituents. The increasing dominance of the amorphous phase at higher temperatures is a key indicator of ash stabilization, as the glassy matrix can effectively immobilize hazardous elements by incorporating them chemically into its disordered structure.

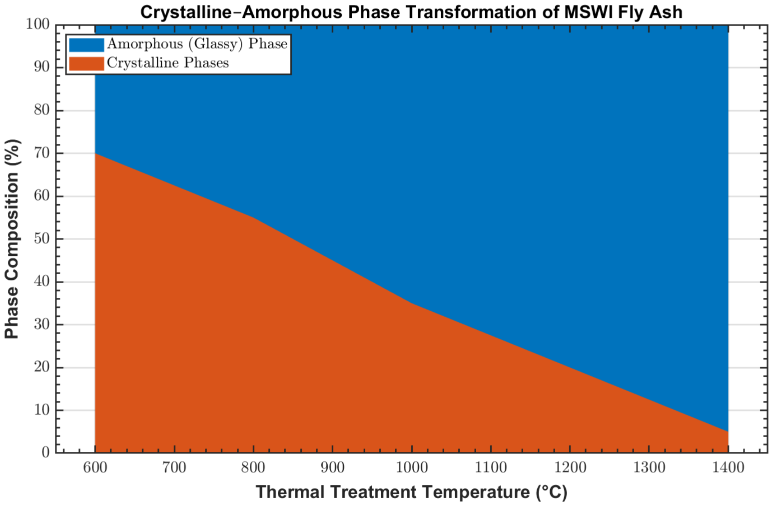


Fig.17 Crystalline - Amorphous Phase Transformation

C. Stabilization/Solidification Treatments

Growing scientific interest has been directed toward the development of environmentally friendly stabilization methods for immobilizing hazardous constituents in waste materials. Stabilization is a common procedure in which wastes are combined with binders to contain pollutants and reduce their dissolution through chemical and physical mechanisms. Following treatment, the hazardous waste can be transformed into materials suitable for disposal in engineered landfills. In recent years, China released the first technical specification aimed at reducing fly ash pollution from incinerators. This guideline allows properly treated fly ash to be recycled and reclassified as non-hazardous waste. Washing, solidification, and landfill disposal are among the most widely used methods for treating fly ash. Although cement is the most commonly used stabilizer for solidification, alternative materials such as silicates, hydroxides, carbonates, sulfides, and phosphates have recently been investigated to mitigate the environmental impacts associated with chemical substances used in fly ash treatment technologies.

Therefore, substituting alternative stabilizers for cement is essential to reducing the overall ecological impact of the treatment process. For example, sodium hydroxide can reduce the global warming potential by approximately half. However, increases in environmental impact indicators such as land use and human toxicity are largely attributed to the production of chemical activators. Carbon dioxide is another stabilizer that enables effective carbonation of fly ash, thereby reducing its environmental impact. Consequently, it remains common practice to stabilize fly ash using cement or other hydraulic binders and subsequently dispose of it in above-ground non-hazardous waste landfills, even though this approach substantially increases the total volume of material requiring disposal.

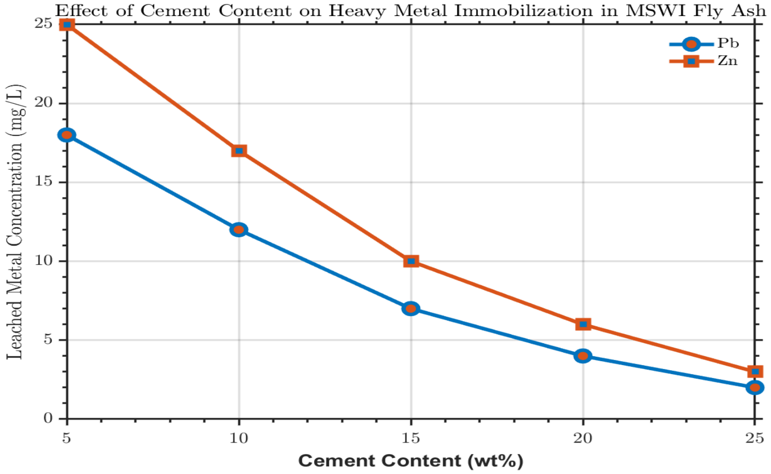


Fig.18 Effect of Cement on Heavy Metal Immobilization

VII. CONCLUSION

This research has systematically examined MSWI fly ash (FA) as a critical by-product of modern waste-to-energy systems. Fly ash is typically classified as hazardous waste due to its high concentrations of toxic metals, chlorides, and persistent organic pollutants. Its composition is highly variable—shaped by waste input, incinerator type, and air pollution control systems—yet it consistently embodies a dual identity: a hazardous pollutant requiring stringent management and a potential reservoir of valuable materials. A review of global regulatory frameworks reveals diverse approaches, ranging from the stringent leaching limits enforced in the EU and Japan to the risk-based TCLP standard used in the USA. Despite regional differences, a clear international trend is emerging in which regulatory focus is shifting from solely ensuring safe landfilling toward enabling and promoting material recovery under strict environmental safeguards. The analysis of treatment technologies indicates a clear transition from containment-oriented strategies to resource-recovery-focused solutions. While conventional cement-based stabilization/solidification remains widespread, its substantial carbon footprint has driven the development of greener alternatives such as geopolymers and carbonation. More advanced separation processes, including acid washing and the FLUREC hydrometallurgical method, show strong potential for recovering valuable metals such as zinc and lead, thereby transforming fly ash into a secondary resource. Thermal technologies, such as vitrification, offer robust solutions for destroying organic contaminants and immobilizing hazardous components within a stable, glassy matrix. However, no single technology provides a universal solution. Optimal management strategies are context-dependent, influenced by local ash composition, regulatory requirements, and economic conditions. The future of MSWI FA management lies in integrated treatment chains—for example, washing to remove chlorides, followed by metal recovery, and final stabilization of the residue for construction applications. This combined approach maximizes resource recovery while minimizing hazardous waste generation. Ultimately, transitioning MSWI fly ash from a disposal challenge to a valuable resource is essential for advancing the circular economy. Such a shift reduces landfill dependence, conserves virgin materials, and mitigates long-term environmental risks. Achieving this requires continued technological innovation, supportive regulatory frameworks, and industrial implementation to ensure that waste incineration evolves into a genuinely sustainable component of integrated waste management.

Declaration of Conflicting Interests

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Use of Artificial Intelligence (AI)-Assisted Technology for Manuscript Preparation

The authors confirm that no AI-assisted technologies were used in the preparation or writing of the manuscript, and no images were altered using AI.

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