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Research Progress and Analysis on Utilization and Disposal Technologies of Fly Ash from Municipal Solid Waste Incineration in China

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Abstract

The utilization and disposal of municipal solid waste incineration (MSWI) fly ash have become a major global environmental challenge and a key link in reducing hazardous waste landfill ratios and achieving "Zero-Waste City" construction targets. Based on the actual development of technologies for the utilization and disposal of municipal solid waste incineration fly ash in China, and in accordance with core objectives, key technical methods and environmental risk control requirements, this paper divides the utilization and disposal of municipal solid waste incineration fly ash in China into three stages, namely "safe landfill", "co-disposal" and "full resource utilization". It systematically sorts out the technologies for the utilization and disposal of municipal solid waste incineration fly ash, relevant laws and regulations, and the construction of environmental risk control systems at each stage, analyzes the performance parameters and key influencing factors of different technologies, and dissects the core problems existing in the disposal modes at each stage. This study can provide a reference for the construction of China's "Zero-Waste City", the improvement of the environmental management system for hazardous waste, and the enhancement of the level of utilization and disposal of hazardous waste.

Keywords

Fly ash; Utilization and disposal technology; Hazardous waste; Historical evolution

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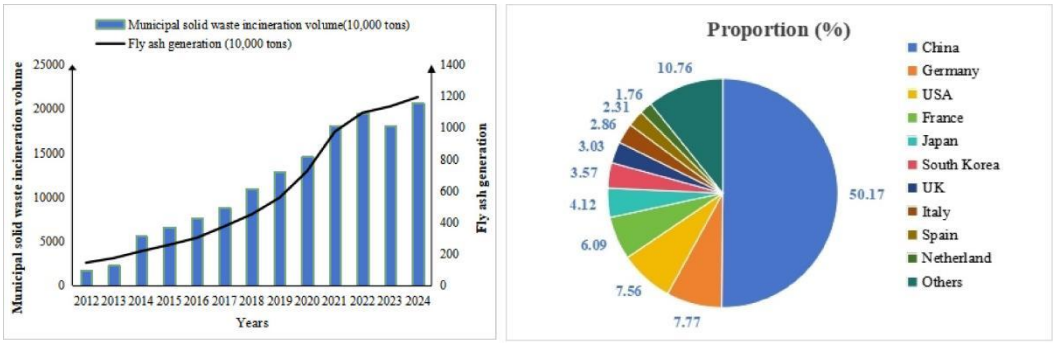
Introduction

Municipal solid waste incineration fly ash (fly ash) consists of particulates captured by the flue gas cleaning system of MSWI facilities and bottom ash settled at the bottom of flue ducts and chimneys[1–4]. MSWI fly ash refers to particulates captured by flue gas cleaning systems, generally accounting for approximately 5% of incinerated waste, while bottom ash consists of furnace bottom residues, approximately 15%. This review focuses exclusively on MSWI fly ash.

As living standards continue to rise, the volume of municipal solid waste generated is steadily increasing. Incineration is one of the most suitable methods for treating municipal solid waste[5–8]. After incineration, the volume of municipal solid waste is generally reduced by more than 90%, and its weight is reduced by more than 70%[9–12]. Among the resulting residual solid waste, bottom ash accounts for approximately 15%, and fly ash accounts for approximately 5%[13,14]. With the large-scale incineration of municipal solid waste, the volume of fly ash generated is also growing rapidly (**Figure. 1**).



(a) (b)

Figure. 1 Fly ash generation and distribution. (a) Analysis of municipal solid waste incineration volume, fly ash generation; (b)comparative proportions across different countries. Data source:National Bureau of Statistics of China. China Statistical Yearbook. (2021 – 2024). Created through Powerpoint.

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The "14th Five-Year Plan for the Development of Urban Household Waste Sorting and Treatment Facilities," jointly issued by the National Development and Reform Commission and the Ministry of Housing and Urban-Rural Development, states that by the end of 2025, China's urban and rural household waste disposal capacity will increase from 580,000 tons per day to approximately 800,000 tons per day. It is estimated that by then, the national fly ash generation will reach about 12 million tons[15].

Globally, fly ash generation is closely linked to the proportion of municipal solid waste treated by incineration. Major developed countries, due to their high incineration rates, all face significant pressure to manage fly ash: Japan, where the incineration rate exceeds 70%[16], incinerated approximately 40 million tons of municipal solid waste in 2022, resulting in about one million tons of fly ash; Germany, a benchmark country for incineration within the EU, reported in official 2023 statistics that its national fly ash generation has stabilized below one million metric tons per year, with over 90% originating from municipal solid waste incineration facilities; although the United States primarily relies on landfilling for waste disposal, it incinerated approximately 35 million metric tons of municipal solid waste in 2018, still generating about 1.6 million metric tons of fly ash, primarily concentrated in densely populated states along the East and West Coasts; the overall production of fly ash in EU countries exhibits a stable and slightly declining trend. Notably, countries such as the Netherlands and Belgium, facing land constraints reuse, achieved a resource utilization rate of over 95% for fly ash.

In recent years, significant progress has been made in research on the resource utilization of fly ash from municipal solid waste incineration, and the number of published papers on fly ash has surged dramatically. Since 2020 alone, the Web of Science has indexed over 8,000 relevant publications, clearly demonstrating the high global interest in fly ash (**Figure. 2**).

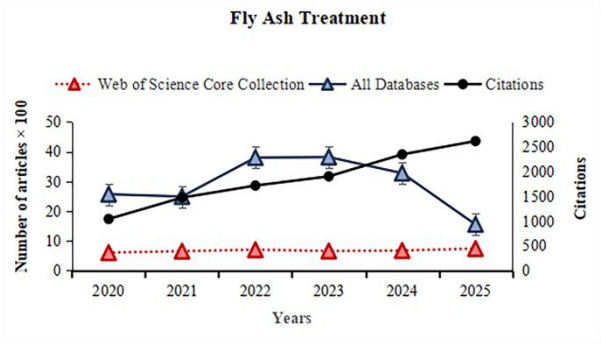

Figure. 2 Trend of paper publication on domestic waste incineration and fly ash production from 2020 to 2025. The literature for this review was collected from Web of Science, covering the period 2020 – 2025. Keywords included "MSWI fly ash," "hazardous waste utilization," "cement kiln co-processing," and "resource recovery." Inclusion criteria focused on studies reporting Chinese technical applications, policies, or engineering cases, while duplicates, non-primary sources, or studies lacking quantitative data were excluded. Created through Microsoft Vision.

Municipal solid waste incineration fly ash has a complex composition (**Figure. 3**), in which three categories of core toxic and hazardous substances are concentrated. First are heavy metals (such as Pb, Cr, and Cd); the leaching concentrations of heavy metals in fly ash often exceed the limits specified in the "Identification Criteria for Hazardous Wastes — Leaching Toxicity" (GB 5085.3-2007)[17], and toxicity control is primarily achieved through methods such as solidification/stabilization, high-temperature lattice encapsulation, and chemical chelation[18–20]. Second, dioxin-like persistent organic pollutants (POPs); dioxin levels in fly ash generally range from 0.034 ng TEQ/g to 7.530 ng TEQ/g[21,22], and are removed by adsorption onto activated carbon following incineration[23]. Third, soluble salts: the salt content in fly ash ranges from 10% to 30%, and desalination and separation are typically achieved through multi-stage washing and evaporation crystallization processes[24–26].

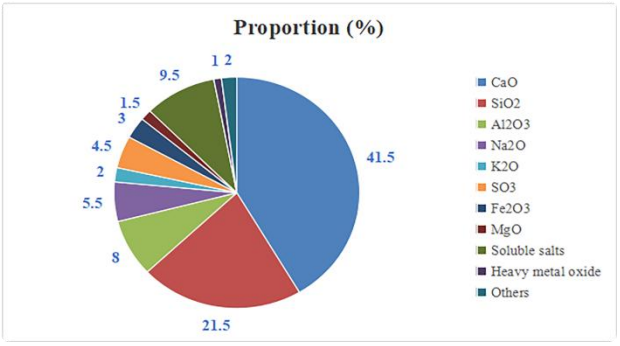

Figure. 3 Proportion of main components in municipal solid waste incineration fly ash. Created through Powerpoint.

To promote the utilization and disposal of fly ash, the State Council's "Implementation Plan for Reforming the Supervision and Utilization/Disposal Capabilities of Hazardous Waste" proposes to "focus on researching and demonstrating applicable technologies for the utilization and disposal of hazardous waste, such as fly ash from municipal solid waste incineration, as well as for the prevention and control of environmental pollution." The Ministry of Ecology and Environment's "Guiding Opinions on Further Strengthening Hazardous Waste Environmental Governance and Strictly Controlling Environmental Risks"[27] sets forth the overall requirement that "by 2030, the proportion of hazardous waste disposed of through landfilling nationwide shall be controlled within 10%" and the primary task that " localities shall, based on actual conditions, promote a gradual reduction in the amount of municipal solid waste incineration fly ash sent to municipal solid waste landfills, and encourage regions with the necessary conditions to take the lead in achieving zero landfilling of municipal solid waste incineration fly ash." Given its hazardous waste classification and the highest proportion of fly ash landfilled, its utilization and disposal have garnered increasing attention. Its disposal development has gradually progressed from three stages of "end-of-pipe harmless landfilling" to "co-disposal" and then to "full resource recovery." This paper systematically reviews the technological frameworks for each stage of fly ash utilization and disposal in China, analyzes the characteristics of fly ash disposal technologies, and provides an in-depth examination of key influencing factors and existing issues, thereby offering a reference for establishing a sound fly ash risk management system.

1. Safe Landfilling

The primary objective of this phase is to address the issue of "safe and environmentally sound disposal." This stage is characterized by a low technical threshold, with the primary goal of controlling heavy metal leaching through solidification/stabilization methods and ensuring environmental risk mitigation. By reducing the risk of contaminant leaching through solidification-stabilization treatment, this approach enables the disposal of fly ash in designated fly ash landfill sections within municipal solid waste landfills[19,28]. It is the earliest and most widely used fly ash disposal technology in China.

Because municipal solid waste incineration fly ash contains high concentrations of heavy metals — such as lead, cadmium, and mercury — as well as the persistent organic pollutant dioxin, direct landfilling poses long-term environmental risks[29–32]. The 2008 revision of the National List of Hazardous Wastes explicitly classified municipal solid waste incineration fly ash as a hazardous waste under the category of incineration residues[33] (HW18; waste code 772-002-18). In 2008, the Ministry of Ecology and Environment revised the "Pollution Control Standards for Municipal Solid Waste Landfills" establishing acceptance criteria for fly ash disposed of in municipal solid waste landfills regarding moisture content, dioxin levels, and heavy metal concentrations. Fly ash that has been treated to meet these requirements may be landfilled in a separate section of a municipal solid waste landfill.

The core technology of this stage is the synergistic treatment of cement solidification/stabilization combined with chelating agents. The typical mixing ratio is fly ash: cement 1:0.2 – 1:0.4, with chelating agent dosage of 2% – 5% of fly ash mass. By mixing fly ash, cement, chelating agents, and water in specific proportions, thoroughly stirring the mixture, and subjecting it to a series of physical and chemical reactions, a slurry is formed and poured into molds[34–36]; during the hydration reaction, through solidification and encapsulation, heavy metals in municipal solid waste incineration fly ash are encapsulated in the hydrated silicates formed after the reaction, taking the form of hydroxides or complexes. Heavy metals are stabilized by physical encapsulation and chemical chelation simultaneously, which effectively reduces leaching risk. After stabilization treatment, the leaching of heavy metals is reduced by 85% – 95%[37], meeting national standards for landfill disposal. Dioxins are mainly physically encapsulated with a removal rate lower than 10%, so their concentration must meet the pre-landfill limit. The removal rate of dioxins is relatively low and must meet pre-landfill concentration requirements; operating costs range from CNY 400 – 600 (approximately USD 56 – 83)/t, with low energy consumption of only 5 – 8 kWh/t. There is no discharge of exhaust gas or wastewater; only solidified waste residue is produced[38]. Chemical solidification achieves a higher degree of heavy metal stabilization in fly ash (where phosphates, sulfides, and other compounds react with heavy metals to form stable compounds) and offers a wider variety of stabilizers. Different agents show obvious selectivity to heavy metals, so composite stabilizers are often required in engineering. However, chemical agents exhibit a certain degree of selectivity in stabilizing heavy metals, making it difficult to stabilize multiple metals simultaneously[39–41]; therefore, a combination of multiple agents is typically required[42–45]. The different fly ash treatment processes and their resulting products are shown in **Figure. 4**.

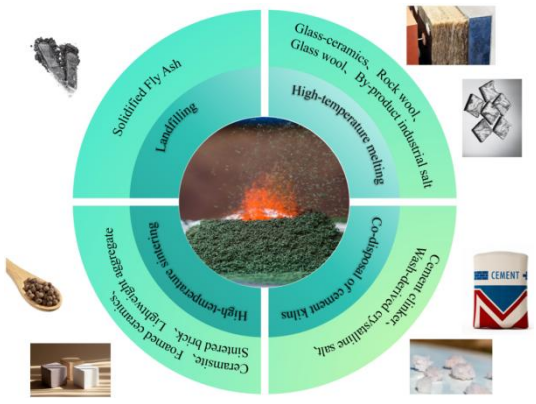

Figure. 4 Different treatment processes for fly ash and their product images after treatment. Created through Powerpoint.

The advantages of fly ash solidification/stabilization treatment include low technical barriers, high processing capacity, and low costs[46,47]; however, it is significantly influenced by factors such as the location of municipal solid waste landfills and transportation distances[48]. At the same time, municipal solid waste landfills have not clearly defined the responsible party for fly ash pretreatment, leading to ineffective oversight and monitoring of treatment outcomes. Some companies are unable to adjust their processes in real time based on the heavy metal concentrations in the fly ash during solidification/stabilization, making it difficult to ensure that the leaching of hazardous substances from the solidified fly ash consistently meets regulatory standards. Fly ash has a complex composition; the selection of chelating agents and their addition ratios both affect the stabilization of heavy metals. The high salt and high chlorine content of fly ash can compromise the structural strength of the cement-based solidification matrix. There is a risk of leaching of heavy metals and inorganic salts over time; insufficient attention has been paid to the stabilization of residual dioxins in fly ash and the risk of toxic leaching, making it impossible to assess the long-term leaching risk of dioxins after landfill disposal, and there is a lack of relevant environmental risk analysis methods and monitoring mechanisms; simultaneously, the volume expansion ratio after fly ash solidification/stabilization is high, occupying a significant amount of land resources[49].

In summary, the long-term practice of solidifying/stabilizing and landfilling fly ash is unsustainable and poses environmental risks; any accident could result in major pollution issues[50–52]. Currently, in some regions of China, such as the eastern regions, existing municipal solid waste landfills are facing capacity constraints, and it is difficult to secure sites and approvals for new landfills; following the implementation of the "Pollution Control Standards for Hazardous Waste Landfills" (GB 18597-2023)[53], site selection for flexible landfills has become more challenging, and fly ash that has not undergone dechlorination struggles to meet the admission requirements for flexible landfills. Rigid landfill disposal is costly and has relatively limited capacity, making it increasingly difficult to "bury fly ash safely."

2. Co-disposal Method

The primary objective of this phase is to achieve the "co-disposal of fly ash" from municipal solid waste incineration. This stage has a medium technical threshold, aiming for partial resource utilization. Environmental risk control focuses on high-temperature decomposition of toxic substances and management of chloride content entering the kiln. Centered on the technology of fly ash washing combined with co-disposal in cement kilns, this initiative aims to demonstrate and promote its widespread application nationwide, thereby enabling the utilization of inorganic elements in fly ash, such as silicon and calcium, as raw materials for cement production.

China has formulated and issued a series of policies, regulations, and standards on municipal solid waste incineration fly ash, gradually establishing a management system for transitioning fly ash from hazardous disposal to resource utilization since 2012. In June 2012, the Ministry of Environmental Protection issued the "Technical Specifications for the Collection, Storage, and Transportation of Hazardous Wastes" (HJ 2025-2012)[54], which clarified environmental management requirements for the collection, storage, and transportation of fly ash to prevent and control environmental risks; in December 2013, the Ministry of Environmental Protection has issued the standard

of "Pollution Control Standards for the Co-disposal of Solid Waste in Cement Kilns" (GB 30485-2013)[55], providing a standard basis for the co-disposal of fly ash in cement kilns; in December 2016, the National Development and Reform Commission and the Ministry of Housing and Urban-Rural Development jointly issued the "13th Five-Year Plan for the Construction of National Urban Domestic Waste Harmless Treatment Facilities", which for the first time explicitly called for "strengthening the treatment and disposal of fly ash" at the national planning level, requiring a 100% utilization and disposal rate for fly ash, and encouraging the research, development, and application of comprehensive fly ash utilization technologies. In the same year, the Ministry of Environmental Protection issued the "Technical Policy on Pollution Prevention and Control for the Co-disposal of Solid Waste in Cement Kilns" (Announcement No. 72 of 2016 by the Ministry of Environmental Protection), providing a policy basis for the co-disposal of fly ash. In particular, the "National List of Hazardous Wastes (2016 Edition)[53]", issued in 2016, explicitly stipulated in its exemption management list that fly ash meeting the requirements of the "Pollution Control Standards for Co-disposal of Solid Wastes in Cement Kilns" (GB 30485-2013)[55] are exempt from hazardous waste management when entering cement kilns for co-disposal; that is, cement enterprises are not required to hold a Comprehensive Hazardous Waste Management License, which has greatly promoted the large-scale promotion and application of the "water washing + cement kiln co-disposal" technology nationwide. Historical trends in the development and changes in fly ash-related policies are shown in **Figure. 5**.

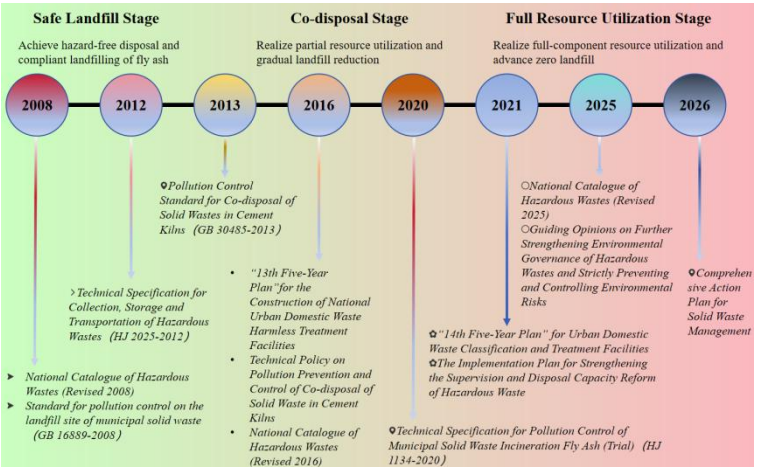

Figure. 5 Historical trend of fly ash policy development and changes. Created through Powerpoint.

The water-washing + cement kiln co-disposal technology is a method in which fly ash is pretreated with water washing to meet cement kiln feed requirements. This route includes dechlorination by three-stage counter-current washing and high-temperature treatment in the cement kiln. Then it undergoes high-temperature decomposition and stabilization of toxic and harmful substances in the cement kiln (**Figure. 6**)[56,57]. First, through three-stage counter-current washing (with a solid-to-liquid ratio controlled at around 1:3), soluble chlorides in the fly ash are dissolved and separated, reducing the soluble chloride content of fly ash to levels suitable for cement kiln feed, in accordance with relevant standards[58,59]. After dechlorination, the fly ash is fed into the cement kiln as a raw material, where, under alkaline high-temperature conditions (> 1450 ℃), dioxins are completely decomposed, and the dioxin emission concentration in the flue gas at the kiln tail is ≤ 0.1 ng I-TEQ/Nm³, complying with the limits set in the "Pollution Control Standard for Co-processing of Solid Waste in Cement Kilns" (GB 30485-2013)[55]. Some heavy metals volatilize into the flue gas and are purified by the exhaust gas treatment system, while some non-volatile heavy metals crystallize and are encapsulated within the crystal lattice of tricalcium silicate minerals[60,61]; inorganic elements such as silicon and calcium are incorporated into the clinker minerals, achieving a resource utilization rate of 80% – 90%[62]. The operating costs of the water washing + cement kiln co-processing process are generally between CNY 800 – 1,200 (approximately USD 112–168)/t[63]. The energy consumption per ton in the water washing stage is 15 kWh – 20 kWh, and the process generates no waste residue for external discharge, producing only a small amount of secondary fly ash that requires recirculation for treatment.

The water washing + cement kiln co-disposal technology achieves the decomposition of toxic and harmful substances in fly ash and the utilization of raw materials through multi-stage water washing for dechlorination and high-temperature treatment in a cement kiln. It offers significant environmental and socioeconomic benefits[64], conserves land resources, reduces costs, and demonstrates good stability, enabling the conversion of elements such as silicon and calcium into cement that meets national standards[65,66]. Among these, the parameters of the water washing process, the operating conditions of the cement kiln, and the effectiveness of fly ash pretreatment are the core factors influencing the efficiency and stability of co-disposal. The solid-to-liquid ratio, number of washing stages, and washing time directly determine the dechlorination effect; the highest dechlorination efficiency is achieved under process parameters of a solid-to-liquid ratio of 1:3 and a three-stage washing process, while excessively long washing times can lead to the leaching loss of calcium and silicon from the fly ash; the temperature, residence time, and sulfur-alkali balance within the cement kiln are critical for dioxin degradation and heavy metal stabilization. Temperatures below 1400℃ result in incomplete dioxin degradation, while an imbalanced sulfur-alkali ratio can easily lead to scaling and blockages in the kiln, affecting clinker production. The drawbacks include the cement kiln's high operational requirements and technical complexity, the limited applicability of the water-washing, evaporation, and crystallization disposal route, and the potential impact of high chlorine content entering the kiln on cement quality and the operation of production facilities. Additionally, the cement kiln's production cycle is significantly influenced by factors such as the building materials market, and the annual operating days of the cement kiln affect the continuous and stable treatment of fly ash, making it prone to instability in co-disposal operations.

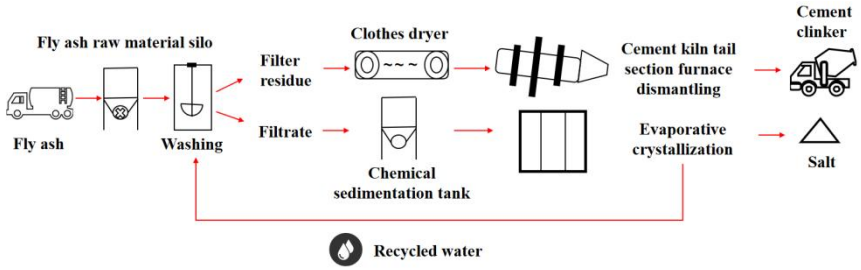

Figure. 6 Process flow diagram of typical fly ash water washing + cement kiln co-processing technology[56,57]. Created through Microsoft Vision.

3. Stage of Full Resource Recovery and Utilization

This stage takes "full resource utilization" as the core objective, aligning with the 14th Five-Year Plan and "Zero-Waste City" hazardous waste landfill control targets. It represents a high technical threshold, aiming for comprehensive utilization of all fly ash components and near-zero landfill. Risk control measures include water-washing pretreatment, thermal processing, and long-term monitoring of recycled products. The goal is to drive the transformation of fly ash disposal from "end-of-pipe disposal" to "resource recycling." Through refined pretreatment and the integration of diversified processes, this initiative aims to achieve the comprehensive utilization of all components — including inorganic minerals and soluble salts — in fly ash. Pilot regions have already launched large-scale demonstration projects, gradually moving toward "near-zero landfill."

China's policy system for MSWI fly ash has gradually evolved from safe landfill control to collaborative disposal and then to full resource utilization, as summarized in **Table 1**. The full-scale resource utilization of municipal solid waste incineration fly ash has met the regulatory and policy conditions for large-scale promotion and application.

Relevant national and local policies are encouraging and promoting the "zero landfill" of fly ash[67-69], with a clear trend toward a comprehensive shift toward resource recovery. This shift reflects a transition from landfill-centric to resource-oriented approaches, and from extensive management to precise management, aiming to advance the resource recovery of fly ash and technological innovation while strictly controlling environmental risks.

During this stage, a wide range of technologies for the resource recovery of fly ash were developed and widely adopted, including fly ash washing/evaporation crystallization + low-temperature pyrolysis + utilization in building materials (**Figure. 7**), washing/evaporation crystallization + high-temperature melting + production of rock wool[20] (**Figure. 8**) or other building materials, and high-temperature sintering of fly ash to produce ceramic aggregates[70] (**Figure. 9**), washing/evaporation crystallization + high-temperature sintering + production of foamed ceramics[71] (**Figure. 10**), as well as the synergistic resource utilization of municipal solid waste incineration fly ash, waste salt, and waste acid (**Figure. 11**), among others. These routes all take washing dechlorination as the prerequisite step. The technical routes are significantly different at this stage. Their core performance parameters are all based on national standard limits, and each process must first undergo thorough water washing to remove chlorine (with a stable dechlorination rate of 90% – 95%). Only the pretreated material can proceed to subsequent resource recovery stages. High-temperature routes can achieve complete dioxin degradation and heavy mineral lattice solidification, while low-temperature routes feature lower energy consumption and cost. The resource utilization rate of full-component utilization routes can reach more than 95%. A critical evaluation indicates that low-temperature pyrolysis and building material utilization offer low energy consumption but limited product value, whereas high-temperature melting and sintering yield high-performance products at the expense of higher energy and equipment costs. Industrial bottlenecks include a lack of standardized equipment, limited market acceptance of recycled products, and insufficient policy incentives for large-scale implementation. This analysis highlights both the opportunities and practical constraints associated with full-component resource recovery of MSWI fly ash.

Table 1. Policy evolution of MSWI fly ash utilization and disposal in China

Year	Document	Core requirement	Management orientation
2008	National Hazardous Waste List	MSWI fly ash classified as HW18 hazardous waste	Safe landfill and stabilization control
2013	GB 30485–2013	Pollution control for cement kiln co-disposal	Standardized co-disposal allowed
2016	Hazardous Waste Exemption List	Eligible fly ash exempted in cement kilns	Large-scale co-disposal promoted
2020	HJ 1134–2020	Whole-process pollution control specification	Standardized utilization and disposal
2021	14th Five-Year Plan for MSW Management	Explore resource utilization of fly ash	Building materials and metal recovery encouraged
2025	Guiding Opinions on Hazardous Waste Governance	Landfill ratio ⩽ 10% by 2030; encourage zero-landfilling	Full resource utilization prioritized

NOTE: MSWI:Municipal Solid Waste Incineration; HW18:HW18 Incineration Disposal of Residual Hazardous Waste (Waste Code 772-002-18).

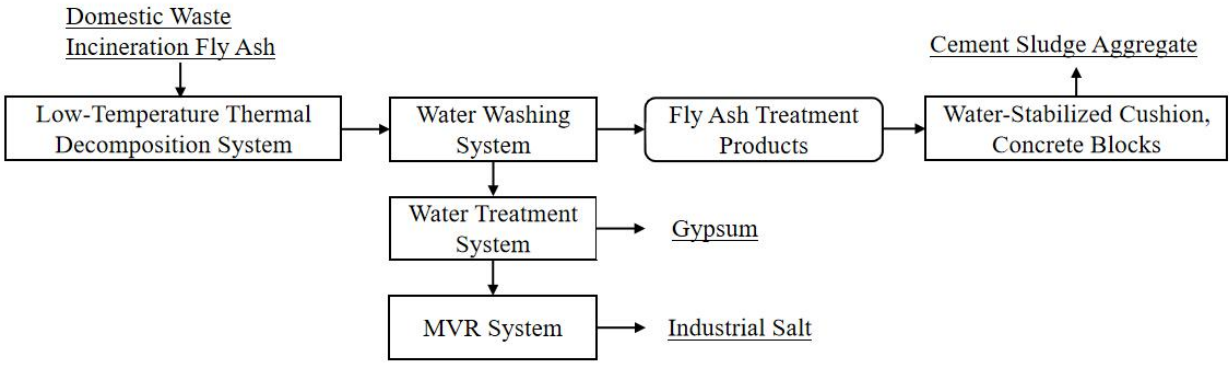

Figure. 7 Technological process flowchart of water washing + low-temperature pyrolysis + building material utilization. MVR:Mechanical Vapor Recompression. Source: Guangzhou Municipal Urban Management and Comprehensive Law Enforcement Bureau. Created through Microsoft Vision.

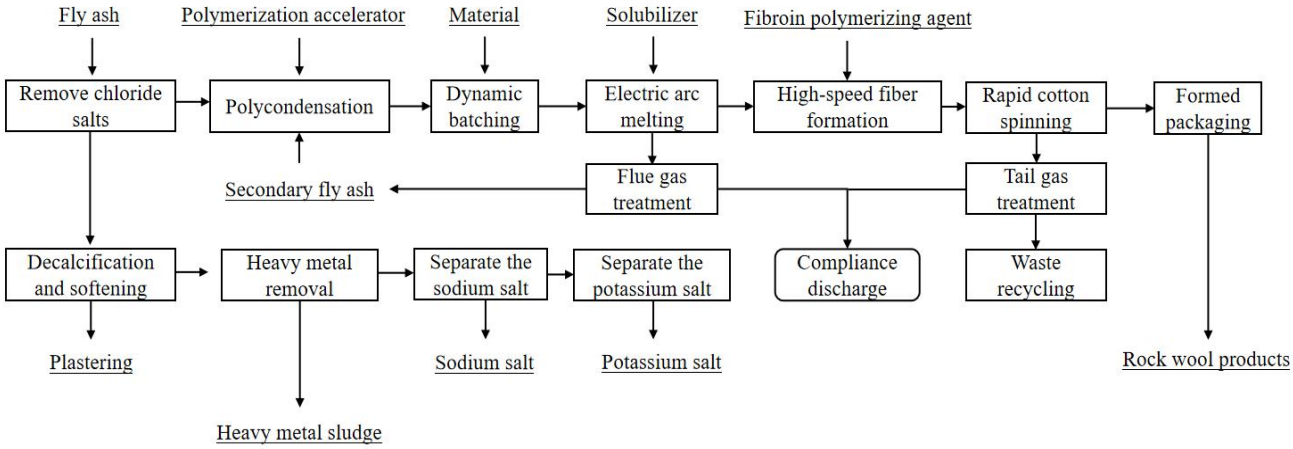

Figure. 8 Process flow diagram of water washing + high-temperature melting + rock wool preparation technology[20]. Created through Microsoft Vision.

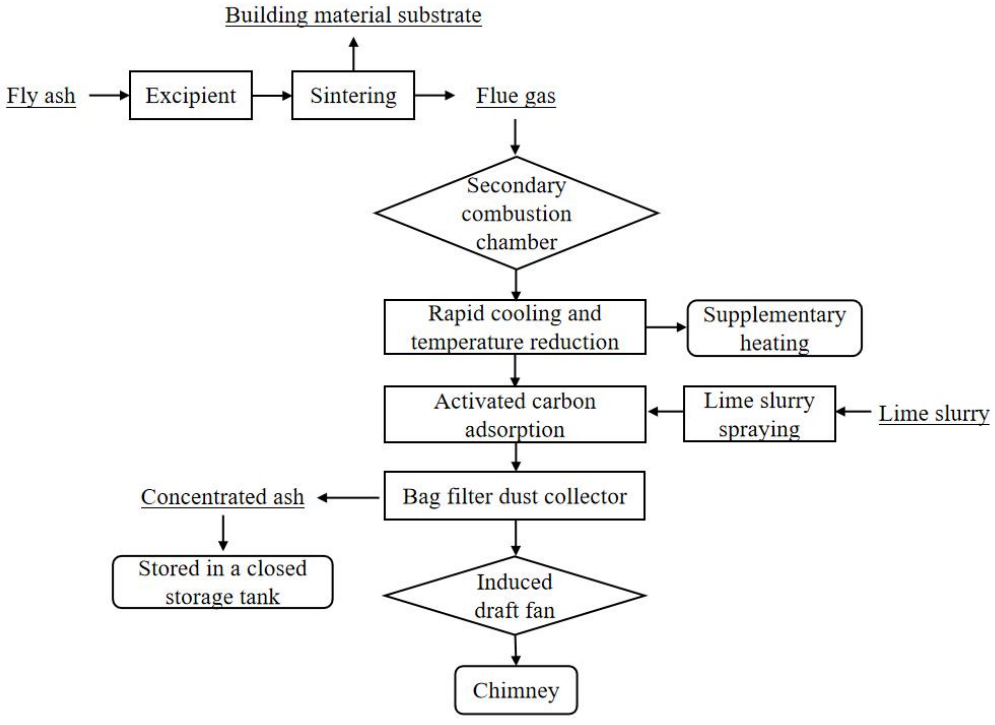

Figure. 9 Fly ash high temperature sintering process for preparing clay particles[70]. Created through Microsoft Vision.

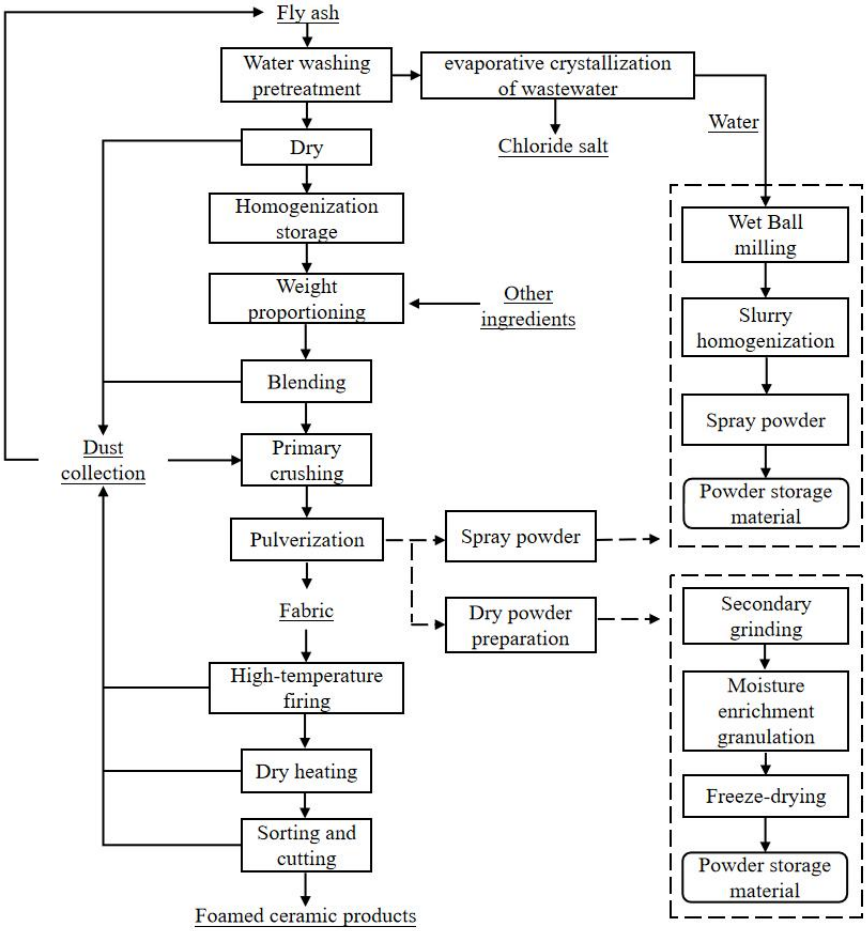

Figure. 10 Water wash/evaporation crystallization + high temperature sintering + preparation of foaming ceramics technology process flow[71]. Created through Microsoft Vision.

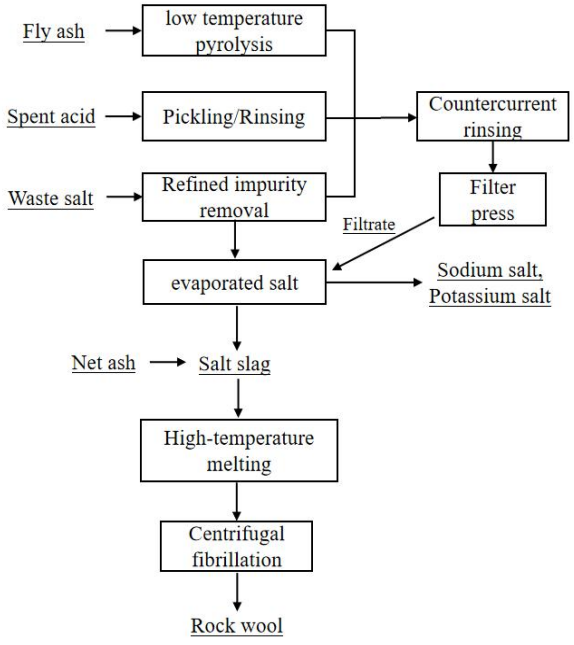

Figure. 11 Technological process diagram of collaborative resource utilization of fly ash, waste salt, and waste acid. Created through Microsoft Vision.

Compared to traditional methods such as landfilling in dedicated zones at municipal solid waste landfills or co-processing via washing and cement kilns, the technology for the comprehensive utilization of fly ash offers the advantage of avoiding the large-scale land use associated with landfilling after solidification/stabilization[72,73]. Full resource routes achieve a higher volume reduction rate and better long-term environmental safety. Fly ash treatment facilities can operate continuously and stably over the long term, produce a diverse range of resource-recycled products, and further expand disposal channels and application scenarios. Melting and sintering routes have higher product performance but higher energy consumption, while low-temperature pyrolysis and synergistic routes have lower cost but relatively lower product added value. However, certain challenges remain: the market size for construction materials such as expanded clay aggregates, lightweight aggregates, and rock wool — produced through high-temperature melting and sintering of fly ash — is small, and the market capacity for these products is limited[74]; standards and regulations for fly ash, as well as risk control systems, are not yet fully established[22]; and aside from high-temperature vitrified products, there is a lack of clear guidelines regarding the disposal and utilization pathways for other fly ash resource recovery products. The technical and economic differences among different routes directly determine their engineering applicability and promotion potential. The advantages and disadvantages of different municipal solid waste incineration, fly ash utilization and disposal technologies are shown in **Table 2**, and a comparison of relevant indicators for fly ash treated by different processes is presented in **Figure. 12**.

Table 2. Comparison of advantages and disadvantages of different treatment processes for domestic waste incineration fly ash. CNY 1 (approximately USD 0.15)

Process Route	Cement Solidification/Stabilization & Chelation + Landfill	Water Washing + Cement Kiln Co-disposal Technology	Resource Utilization			Synergetic Resource Utilization Technology
			Water Washing + High-temperature Melting	Water Washing + High-temperature Sintering	Water Washing + Low-temperature Pyrolysis or Low-temperature Pyrolysis + Water Washing	
Operating Cost (Yuan/ton)	400–600	800 ~ 1200	> 3000	1500 ~ 2000	800 ~ 1100	⩽ 800
Temperature Range	/	> 1450 ℃	1400 – 1650 ℃	900 – 1250 ℃	300 – 500 ℃	350 ~ 500 ℃ (low-temperature pyrolysis for regenerated products)
Products	None	Water-washed crystalline salt, cement	Water-washed crystalline salt, rock wool, vitreous products	Water-washed crystalline salt, sintered products such as ceramsite	Water-washed crystalline salt, products for building material utilization	Admixture, building gypsum, whisker, sodium chloride, potassium chloride, etc.
Operation CostLevel	Low	Relatively low	Relatively High	High	Low	Relatively low
Advantages	Low technical threshold, large treatment capacity, low processing cost	Relatively low comprehensive cost, sound pollution control standard system, realization of raw material utilization of partial components in fly ash	Complete harmlessness of fly ash, sound pollution control standard system	Realization of raw material utilization of fly ash	Relatively low comprehensive cost, high resource utilization rate, wide application range of resource utilization products	Relatively low comprehensive cost, safe removal of pollutants, realization of full resource utilization of fly ash; simultaneous solution to the utilization and disposal problems of waste acid and waste salt
Disadvantages	High volume expansion ratio, occupation of a large amount of land resources, potential long-term environmental risks	Restricted by cement production cycle, generation of secondary fly ash during co-disposal	High energy consumption, large equipment investment, to-be-expanded consumption channels for building material raw materials	High energy consumption, large equipment investment, to-be-expanded consumption channels for building material raw materials	High energy consumption, large equipment investment, to-be-expanded consumption channels for building material raw materials	Complex process flow, requiring professional operation and management personnel

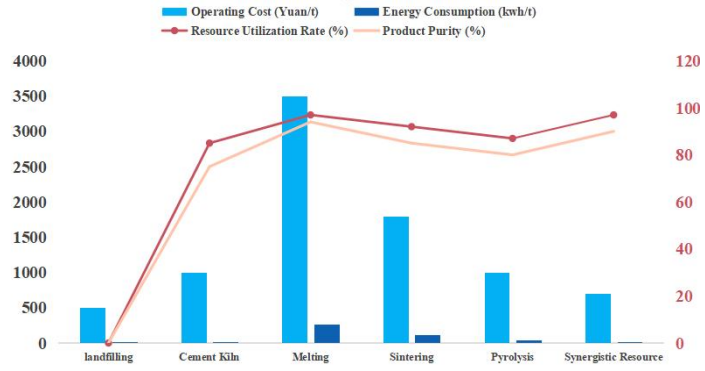

Figure. 12 Comparison of relevant indicators for different treatment processes of municipal solid waste incineration fly ash. Created through Excel.

Issues at the technical, market, standards, and institutional levels are interlinked, making rapid, large-scale implementation difficult. On the technological front, there is an imbalance in economic viability. Aside from co-processing for resource recovery, the operating costs of other processes are relatively high. Furthermore, equipment has not yet been standardized or produced on a large scale, and the processing capacity of a single unit falls far short of the volume of fly ash generated. On the market side, influenced by perceptions of hazardous waste traceability, the market acceptance of resource recovery products is low, their added value is limited, and their application scenarios are narrow, creating a dilemma in which products can be produced but cannot be sold. On the policy and institutional side, there is a lack of targeted incentive policies and market-based payment systems. Revenue from product sales is insufficient to cover disposal costs, resulting in severely low motivation among enterprises to independently advance resource recovery. Additionally, due to the absence of standards and simplified refining processes at some enterprises, the yield of salt produced as a byproduct of washing accounts for only 20% – 30% of fly ash[75,76]. Consequently, true full-scale resource recovery has not been achieved, making this the core bottleneck constraining the industry's development.

4. Conclusion and Prospect

Currently, China's economic and social development has entered a phase of high-quality development characterized by accelerated greening and decarbonization. Driven by the construction of zero-waste cities and the national target to limit hazardous waste landfilling to less than 10% of total disposal, the recovery of fly ash has become a major trend. Key research priorities moving forward include upgrading fly ash washing processes, developing efficient and energy-saving desalination technologies, and reducing pretreatment costs. Developing large-scale, standardized equipment for fly ash resource recovery to increase the processing capacity of individual units and reduce energy consumption per unit; encouraging the synergistic application of multiple technologies, such as the co-recycling of fly ash with waste salt, waste acid, and industrial waste residues, to achieve "treating waste with waste," thereby enhancing resource utilization rates and economic benefits; establishing and improving environmental risk assessment standards and methods for fly ash resource utilization, organizing the revision of technical standards and specifications for pollution control during the fly ash utilization process and for its products, and clarifying quality requirements and application scenarios for resource-recovered products (**Figure. 13**). Furthermore, it is necessary to strengthen environmental risk assessments covering the entire life cycle of fly ash resource utilization, integrate the products of resource utilization into the circular economy system, and ultimately achieve the goals of "harmonization, reduction, and resource utilization" for fly ash, ensuring that fly ash resource utilization technologies are technically achievable, economically viable, risk-controllable, and institutionally acceptable. This complex undertaking requires collaboration among multiple stakeholders, including governments, enterprises, and research institutions, to jointly drive technological progress and industrial upgrading. Through technological breakthroughs, fly ash can be successfully transformed into a useful resource, thereby supporting China's hazardous waste environmental management and the development of "zero-waste cities."

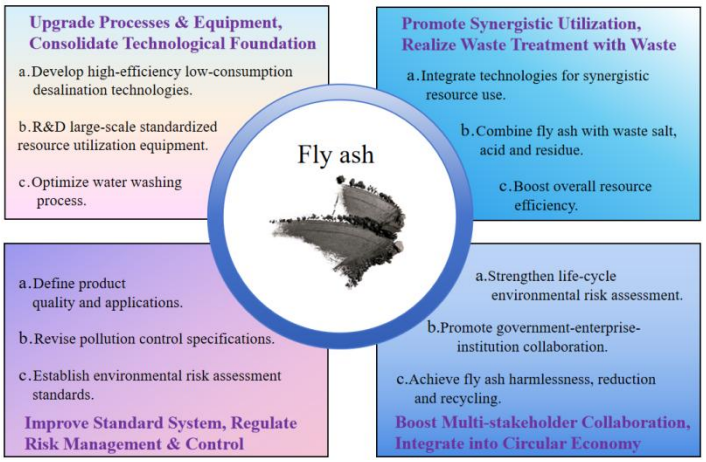

Figure. 13 Future development trends and prospects of fly ash. Created through Microsoft Vision.

Author Contributions

All authors contributed to the study conception and design. Yi He: conceptualization, investigation, writing—original draft, writing—review and editing, formal analysis. Tianlai Zhou: writing—review and editing. Tao Wang: supervision, writing—review and editing. Yang Zheng: supervision, writing—review and editing. Yanping Liu: supervision, resources, writing—original draft, writing—review and editing.

Conflicts of Interest

No potential conflict of interest was reported by the authors.

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