Review

The Current State of Molten Salt Technology for Halogen-Containing Solid Waste Treatmen

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Abstract

Halogen-containing solid wastes have become a global challenge due to their complex composition and potential environmental hazards. Molten salt technology (MST), as an efficient thermal treatment method, utilizes high-temperature molten salts as the reaction medium to effectively degrade organic compounds, capture hydrogen halides, and suppress dioxin formation, while simultaneously enabling metal recovery and carbon reduction. This paper systematically reviews the latest advances in molten salt technology for the treatment of halogen-containing solid wastes, including the reaction characteristics, thermodynamic mechanisms, and applicability of alkaline, carbonate, nitrate, and composite molten salt systems. Through a multi-criteria analysis framework, the advantages and disadvantages of different molten salt systems are compared, and optimized technical routes are proposed for mixed waste streams. The study reveals that the Li_2CO_3-Na_2CO_3-K_2CO_3 ternary carbonate system exhibits excellent performance in organic destruction and removal efficiency and halogen capture, while the NaOH-KOH low-melting-point system offers advantages in energy consumption and equipment simplicity. The innovation of this work lies in the first proposal of a "multi-criteria comparison framework" and the identification of future research priorities. This study provides academic insights and technical guidance for green hazardous waste management and promotes the transition toward a circular economy.

Keywords: molten salt technology, halogen-containing solid waste, hydrogen halide capture, multi-criteria analysis

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Introduction

Halogen-containing chemicals are widely used in industrial production and everyday life due to their ability to significantly enhance the performance of chemical products [1-4]. The incorporation of halogens into plastics, for instance, improves both their mechanical and thermal properties. Studies by Ikeeze et al. and Jandric et al. [5, 6] indicate that brominated flame retardants are commonly added to printed circuit boards and plastic casings in electronic devices to prevent spontaneous combustion. The presence of halogens complicates the disposal of these wastes, as improper handling can lead to severe environmental hazards [7, 8]. The rapid advancement of electronic technology has not only accelerated the introduction of new electronic products but also significantly shortened their replacement cycles, leading to an increase in waste electrical and electronic equipment [9-12].

Kumar et al. [13] reports that nearly 48 million tons of e-waste are generated annually, with this volume growing rapidly. Although waste printed circuit boards constitute only 3-7% of total e-waste, the sheer scale of electronic waste results in millions of tons of WPCBs being produced [14]. Bromine flame retardants are commonly used in electronic products, which further complicates their disposal. Improper handling of these materials can result in severe environmental contamination and pose significant risks to public health [15-17]. Polyvinyl chloride (PVC) plastic is widely used due to its mechanical properties, making it one of the most prevalent plastic types in industrial applications. PVC accounts for 12% of the global demand for plastic products, marking it as one of the highest-volume plastics produced worldwide [18-21]. However, the degradation of PVC releases toxic substances and contributes to the issue of white pollution, creating significant environmental concerns. Other types of halogen-containing solid wastes that can be treated by molten salt technology include trichlorobenzene [22], hexachlorobenzene [23], halogen-containing solvents [24, 25], propellants [26, 27], energetic materials [28, 29], and mixing halogen-containing solid wastes. In the MST process, different kinds of solid waste are fed into the molten salt bath, where the organic matter is converted into CO_2 and steam, and the halogen forms HX, which is absorbed by the molten salt. Stewart et al. [30] reported that nearly 99.99% of organic matter can be removed. Furthermore, Griffiths and Volkovich [31] noted that catalyst-enhanced MST has been applied in areas such as the treatment of scrap tires, nuclear fuel, and concentration of fission products.

The current treatment methods for halogen-containing solid waste, along with their respective advantages and disadvantages, are summarized in Table 1. Conventional methods such as incineration, pyrolysis, and landfilling all have certain limitations in terms of treatment efficiency or environmental friendliness. Although incineration can achieve thorough volume reduction, it suffers from severe emissions of dioxins and hydrogen halides. Pyrolysis allows partial recovery of energy products but exhibits low halogen removal

Table 1. Disposal methods of halogen-containing solid waste.

Disposal method	Advantages	Disadvantages	Reference
Landfill	Simple to operate; Large treatment capacity; Inexpensive	Fails to recover valuable resources; Increases the toxicity of the leachate; Pollutes the environment	[32] [33] [34]
Incineration	Recovery of heat energy; Easily separate the different components after incineration	Production of brominated dioxins; Pollution to the environment; Dealing with pollutants consumes a lot of energy	[35] [36] [37]
Pyrolysis gasification	Effectively dispose of organic components; Recover fossil energy	High investment cost for the equipment; Halides are difficult to handle	[38] [39] [40] [41]
Pyrometallurgy	Complete oxidative degradation of the organic matter; High metal recovery efficiency	High energy consumption in the disposal process; High investment costs for equipment	[42] [43] [44]
Dechlorination treatment	Reduce cost; Simplify the process; Simplified operation difficulty	The amount of HCl and PCDD/Fs decreased greatly; Recovery of valuable components	[45] [46] [47] [48]
Mechanical separation	Simple to operate; Low cost; Metals recovered directly	Some valuable components were lost; Organic components need to be disposed of	[49] [50]
Supercritical fluid	Dissolve refractory oxides; High metal recovery	Need to be pretreated; High equipment investment	[51] [52] [53]

efficiency for wastes containing chlorinated plastics. Plasma technology, on the other hand, is costly and energy-intensive, making large-scale application challenging. Molten salt technology uses high-temperature molten salts as the reaction medium, which can absorb hydrogen halides, stabilize metal ions, and effectively suppress dioxin formation, demonstrating clear environmental and economic potential. However, there are very few studies that have summarized the research on the treatment of halogen-containing solid waste using molten salt.

Yao et al. and Lin et al. [54, 55] suggest that molten salt treatment is a promising and stable approach for the thermal disposal of organic-containing solid waste. During the process, acidic gases such as HX and SO_2 are adsorbed by the molten salt within the reactor, thereby minimizing the release of halogens in the gaseous products and inhibiting the formation of PCDD/Fs. Furthermore, insoluble components like copper are deposited at the bottom of the salt reactor, allowing for the separation and recovery of metals through water washing post salt discharge. Lantelme et al. and Lovering et al. [56, 57] have explored the application of molten salt technology in various domains, including energy, waste management, coatings, and materials [58, 59]. Despite being composed of inorganic compounds, molten salts exhibit altered physical and chemical properties in their molten state, such as solubility, electrical conductivity [60, 61], thermal conductivity [62], and adsorption capacity.

The objectives of this study are to systematically evaluate the performance of molten salt technology in the safe and resource-efficient treatment of halogen-containing solid waste, compare the reaction characteristics, pyrolysis mechanisms, and applicability of different molten salt systems, including alkaline, carbonate, nitrate, and composite systems, and propose optimal technical routes and future research directions for complex halogen-containing waste streams through multi-criteria analysis encompassing energy consumption, efficiency, economic feasibility, and environmental benefits. The main innovations and contributions of this work are the first integrated comparison of thermodynamic mechanisms, environmental benefits, and economic performance across molten salt systems, the proposal of a multi-criteria comparative framework suitable for mixed halogen-containing wastes, and the identification of future research priorities and policy recommendations for molten salt technology.

Results and Discussion

History of Molten Salt Technology

Molten salt technology can be traced back to the 1950s, when it was first employed by the U.S. Atomic Energy Commission for nuclear fuel reprocessing.

It was subsequently extended to coal gasification and the harmless treatment of organic wastes. By the 1980s, the technology was applied by Rockwell for organic waste treatment, forming the prototype of Molten Salt Oxidation. In the 21st century, driven by stricter environmental regulations and limits on dioxin emissions, catalytically enhanced and composite molten salt systems have become research focal points. In recent years, molten salt technology has gradually expanded from treating single waste streams, such as PVC or electronic waste, to the co-processing of mixed organic wastes and halogen-containing hazardous wastes, demonstrating broad application prospects [63-69].

Characteristics

Molten salts possess several unique properties. They are ionic liquids consisting of cations and anions, where the cations are primarily alkali metal ions, and the anions typically include chloride, nitrate, and carbonate ions. This composition grants molten salts excellent thermal conductivity. Molten salts exhibit both high thermal and chemical stability, with operational temperature ranges spanning 200-1000°C. Molten salts demonstrate high solubility for various substances, a trait that enhances their application potential. These properties highlight the advantages of molten salt technologies [70-73]. However, Wang et al. [74] notes that the transformation of multiphase flow patterns remains understudied, and further research could provide clearer insights into the molten salt treatment process for solid waste. Yin et al. [75] emphasizes that research on the behavior of inorganic matter in molten salt systems is lacking. Table 2 lists the composition and melting temperatures of various multi-component molten salts.

System Description

The integrated molten salt processing system at Lawrence Livermore National Laboratory is designed to handle organic solid waste, such as plastics, gloves, boots, and rags, as shown in Fig. 1a). According to Hsu [89], the system utilizes molten salt oxidation for waste treatment. The setup comprises several critical subsystems, including a reaction vessel, an exhaust gas treatment unit, a salt recovery system, feed equipment, and a final waste immobilization process [90, 91]. The feed preparation system involves drums for waste reception, centrifuges for solid-liquid separation, and crushers for reducing solid waste size. Inorganic residues accumulate in the molten salt during the process, requiring regular removal and the addition of new salt to maintain efficiency [92, 93]. The molten salt reactor and gas treatment system is shown in Fig. 1b). Solid waste and air are injected into the base of the reactor. As noted by Edwards et al. [94], the reactor, constructed from thick Inconel, is particularly vulnerable to corrosion when the NaCl content in the system is high. The cooler uses two concentric tubes

Table 2. Composition and melting temperature of partially molten salts.

Molten salt composition / mol%	Melting point temperature (ºC)	Reference
44 mol% K_2CO_3: 56 mol% Na_2CO3	710ºC	[76]
71 mol% Na_2CO_3: 29 mol% K_2CO_3	573ºC	[77]
50.6 mol% Na_2CO_3: 49.4 mol% NaCl	623ºC	[78]
8.3 mol% Na_2CO_3: 91.7 mol% NaOH	285ºC	[79]
90.7 mol% KOH: 9.3 mol% K_2CO_3	366ºC	[80]
95.7 mol% KOH: 4.3 mol% K_2CO_3	387ºC	[81]
80 mol% KOH: 20 mol% K_2CO_3	487ºC	[82]
50 mol% Li_2CO_3: 50 mol% Na_2CO_3	405ºC	[83]
44.1 mol% Li_2CO_3: 29.8 mol% Na_2CO_3: 26.1 mol% K_2CO_3	393ºC	[84]
29.4 mol% K_2CO_3: 70.6 mol% NaOH	170ºC	[85]
K_2CO_3	891ºC	[86]
Li_2CO_3	723ºC	[87]
Na_2CO_3	851ºC	[88]

with an air gap, where compressed air circulates to cool the system. The salt recovery system is shown in Fig. 1c). Adamson et al. [95] presents a detailed flow diagram of the salt recovery system. The molten salt recovery efficiency was maintained at approximately 85-90%. The functional flow diagram for ceramic waste form process is depicted in Fig. 1d) [96], which describes this system as incorporating both quality control and process monitoring mechanisms, with appropriate hazard controls integrated throughout ceramic waste processing stages.

Reaction Mechanisms

Under high-temperature conditions, halogens, along with other components like nitrogen and sulfur present in organic waste, are converted into acidic gases, which are efficiently absorbed by the molten salt bath [97,
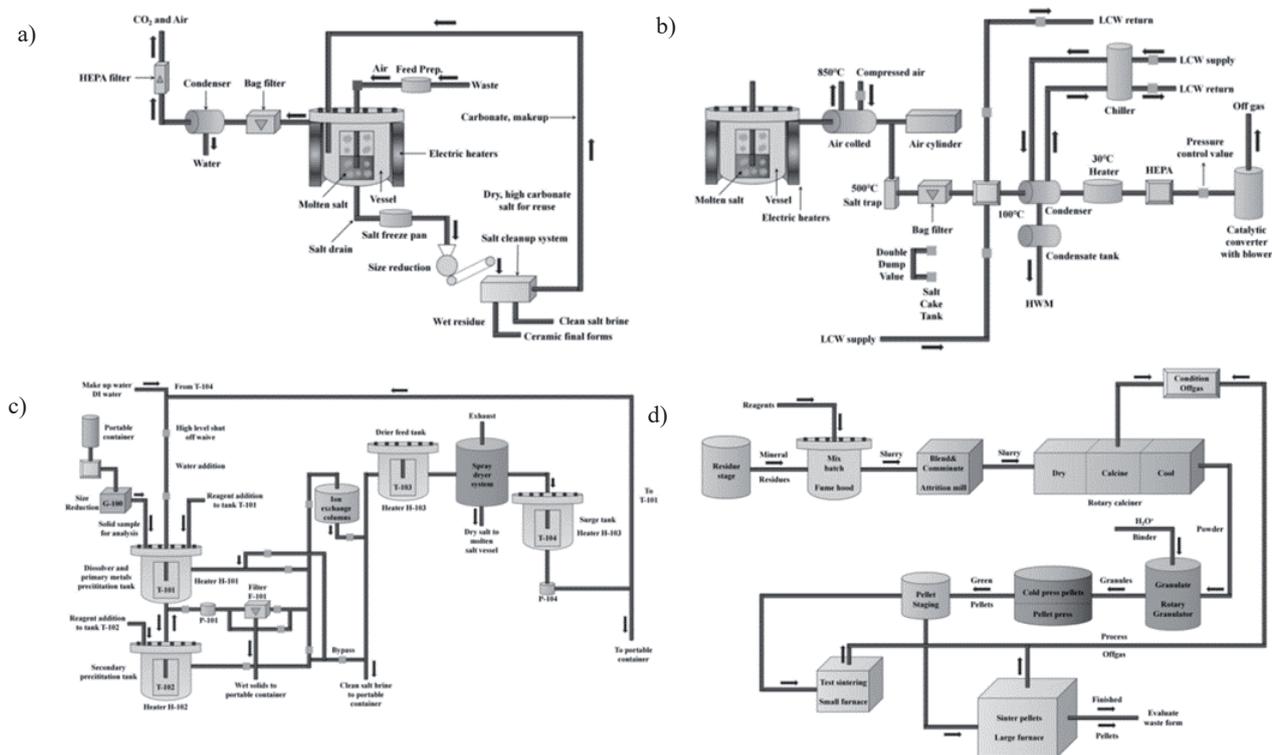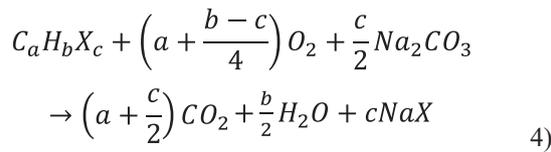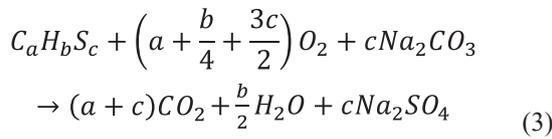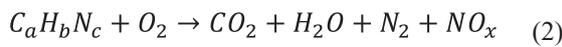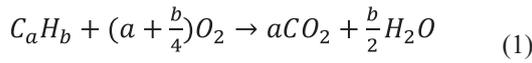

Fig. 1. Integrated molten salt processing system [89, 93, 95, 96].

98]. Wang et al. [99] outlines the chemical treatment mechanism of carbonates involved in this process, represented by a series of Eq. (1)- Eq. (4), where X denotes halogens. These halogens react with salts in the molten bath, ensuring they are contained, thus easing the air treatment process. Copper and Van [100, 101] have investigated the initial phase of organic material degradation in molten sodium carbonate, identifying that hydrogen halides are released during this process. During the ascent of these bubbles, the molten salt effectively captures sulfur, nitrogen, and halogens from the gas, facilitating reactions between the acidic gases and the molten salt.

$$C_aH_b + (a + \frac{b}{4})O_2 \rightarrow aCO_2 + \frac{b}{2}H_2O \qquad (1)$$

$$C_aH_bN_c + O_2 \rightarrow CO_2 + H_2O + N_2 + NO_x \quad (2)$$

$$C_aH_bS_c + \left(a + \frac{b}{4} + \frac{3c}{2}\right)O_2 + cNa_2CO_3$$
$$\rightarrow (a + c)CO_2 + \frac{b}{2}H_2O + cNa_2SO_4 \qquad (3)$$

$$C_aH_bX_c + \left(a + \frac{b-c}{4}\right)O_2 + \frac{c}{2}Na_2CO_3$$
$$\rightarrow \left(a + \frac{c}{2}\right)CO_2 + \frac{b}{2}H_2O + cNaX \qquad 4)$$

Stelman and Gay [102] attempted to elucidate the reaction mechanism, but researchers often posited that molten salt merely acted as a catalyst for the process. It was not until approximately 2005 that Griffiths et al. [69] proposed that molten carbonates possess unique chemical properties, primarily attributed to the availability of excess oxygen, which facilitates the conversion of carbonate ions into peroxide and superoxide ions. The specific reactions involved are illustrated in Eq. (5) and Eq. (6).

$$O_2 + 2CO_3^{2-} \rightarrow 2O_2^{2-} + 2CO_2 \qquad (5)$$

$$3O_2 + 2CO_3^{2-} \rightarrow 4O_2^- + 2CO_2 \qquad (6)$$
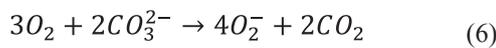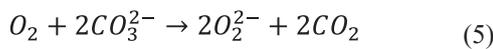
Griffiths et al. [69] also demonstrated that the incorporation of nitrate ions increases the concentration of peroxide ions in molten salt. Furthermore, nitrite ions react with superoxide to produce nitrate. The reactions involved are represented in Eq. (7) and Eq. (8). Notably, it was found that under conditions of excess oxygen, elemental nitrogen can be ultimately converted into nitrate, even in the absence of additional nitrate.

$$2NO_3^- + O_2^{2-} \rightarrow 2NO_2^- + 2O_2^- \qquad (7)$$

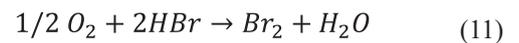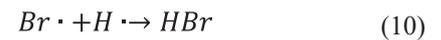$$NO_2^- + O_2^{2-} \rightarrow NO_3^- + O_2^- \qquad (8)$$
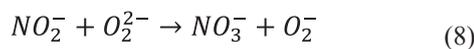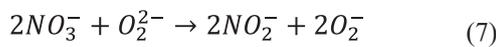
Research conducted by Griffiths et al. [69] indicates that plastics, paper, and cotton can be completely oxidized in a carbonate molten salt containing 5% potassium nitrate. In the $LiCO_3$-$NaCO_3$-KCO_3 treatment system, tire samples yield substantial amounts of carbon, oil, and organic compounds in the off-gas. However, the addition of KNO_3 to the ternary carbonate molten salt system effectively removes pyrolytic oil and organic species, thereby optimizing the treatment process [103]. The current optimal approach for halogen-containing waste management involves a recommended treatment route of "mixed waste→molten salt co-pyrolysis→halogen fixation→metal recovery→waste salt regeneration and recycling".

Applications

Waste Printed Circuit Boards

Flandinet et al. and Wang et al. [104, 105] examined the molten salt treatment process for waste printed circuit boards using a KOH-NaOH eutectic mixture, as illustrated in Fig. 2a). In comparison to carbonate mixtures that operate at elevated temperatures of 850ºC, the KOH-NaOH eutectic mixture functions at a significantly lower temperature of 350ºC. The results demonstrated that the primary gas produced in the reactor was hydrogen, which could be utilized as fuel under a maintained neutral atmosphere. Additionally, all halogens were successfully absorbed by the molten salt. Analysis of the gas composition post-treatment revealed an average hydrogen concentration of 27.8%, while nitrogen and methane concentrations were 2.0% and 1.8%, respectively. Lin et al. [106] studied WPCBs' treatment in a ternary carbonate system (Li_2CO_3-Na_2CO_3-K_2CO_3), with a schematic shown in Fig. 2b). The eutectic mixture (33.4 wt% K_2CO_3, 33.3 wt% Li_2CO_3, and 33.3 wt% Na_2CO_3) had a low melting point of 393°C. Brominated flame retardants were released into the gas phase via a bromine transfer pathway, which influenced the formation of brominated dioxins/furans. During the high-temperature reaction, 99.9% of bromine or hydrogen bromide transitioned into the gas phase, as described in reactions from Eq. (9) to Eq. (11).

$$2Br \cdot \rightarrow Br_2 \qquad (9)$$

$$Br \cdot + H \cdot \rightarrow HBr \qquad (10)$$

$$1/2\ O_2 + 2HBr \rightarrow Br_2 + H_2O \qquad (11)$$

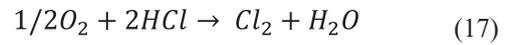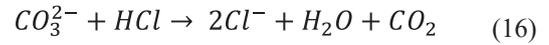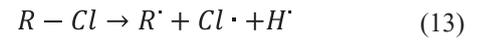More than 99.95% of the halogen is effectively captured in the molten salt. For nitrogen-containing organic compounds, the reactions facilitated by sodium carbonate in the molten salt can be represented by Eq. (12) [107]. As the temperature rises, the emission of nitrogen oxides initially decreases and then increases, with a minimum observed at 650ºC. Within the temperature range of 600-750ºC, the brominated

flame retardants present in WPCBs are completely decomposed to form HBr and Br₂, which are then neutralized within the molten salt.

$$C_aH_bN_c + O_2 + Na_2CO_3 \rightarrow CO_2 + H_2O + N_2$$
$$+NaNO_3 + NO_x \quad (12)$$
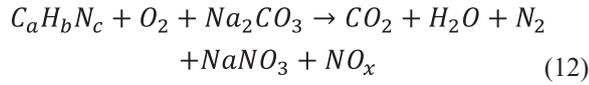
PVC Plastics

PVC plastics are extensively utilized in daily life due to their exceptional mechanical strength and durability [108-112]. A schematic of the lab-scale treatment process for PVC plastics using molten salt technology is depicted in Fig. 2c) [113]. The molten salt reactor is heated to a maximum of 1200ºC. When PVC plastics are introduced into the reactor, halogens are converted into gaseous and acidic forms, such as hydrogen chloride and hydrogen fluoride, along with trace amounts of free halogen. In the molten Na_2CO_3 system used for treating PVC pipes containing 44.6% chlorine, no detectable chlorine was present in the emissions, and the concentration of hydrochloric acid did not exceed 5 ppm. However, the collection efficiency for sulfur was lower compared to chlorine and fluorine, with sulfur dioxide (SO_2) emissions influenced by the amount of excess air [114, 115]. The reaction mechanism follows a process where the chlorine released from PVC under high temperatures in the molten salt system is neutralized and stabilized, as detailed in Eq. (13) to Eq. (18).

$$R - Cl \rightarrow R^. + Cl \cdot + H^. \quad (13)$$

$$Cl \cdot + H^. \rightarrow HCl \quad (14)$$

$$Cl \cdot + Na^. \rightarrow NaCl \quad (15)$$

$$CO_3^{2-} + HCl \rightarrow 2Cl^- + H_2O + CO_2 \quad (16)$$

$$1/2O_2 + 2HCl \rightarrow Cl_2 + H_2O \quad (17)$$

$$CO_3^{2-} + Cl_2 \rightarrow Cl^- + ClO^- + CO_2 \quad (18)$$
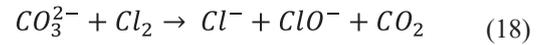
The treatment of halogen-containing PVC plastics can be achieved using metal nitrates and alkaline earth compounds [116]. When PVC is combined with $Ca(NO_3)_2$ and $NaNO_3$ and heated to its maximum melting temperatures of 260ºC and 375ºC, respectively, hydrochloric acid is released due to the thermal decomposition of PVC at around 200ºC. Studies have shown that approximately 35% of the chlorine from PVC is converted into soluble chlorine. Additionally, calcium nitrate reacts with acetylene, and nearly all the calcium nitrate is consumed in this reaction sequence, as illustrated by Eq. (19) to Eq. (22). The reaction system of $Ca(NO_3)_2$-$Ca(OH)_2$ molten salt within the temperature range of 20ºC to 500ºC is depicted in Fig. 2d) [117].

$$C_2H_3Cl \rightarrow C_2H_2 + HCl \uparrow \quad (19)$$

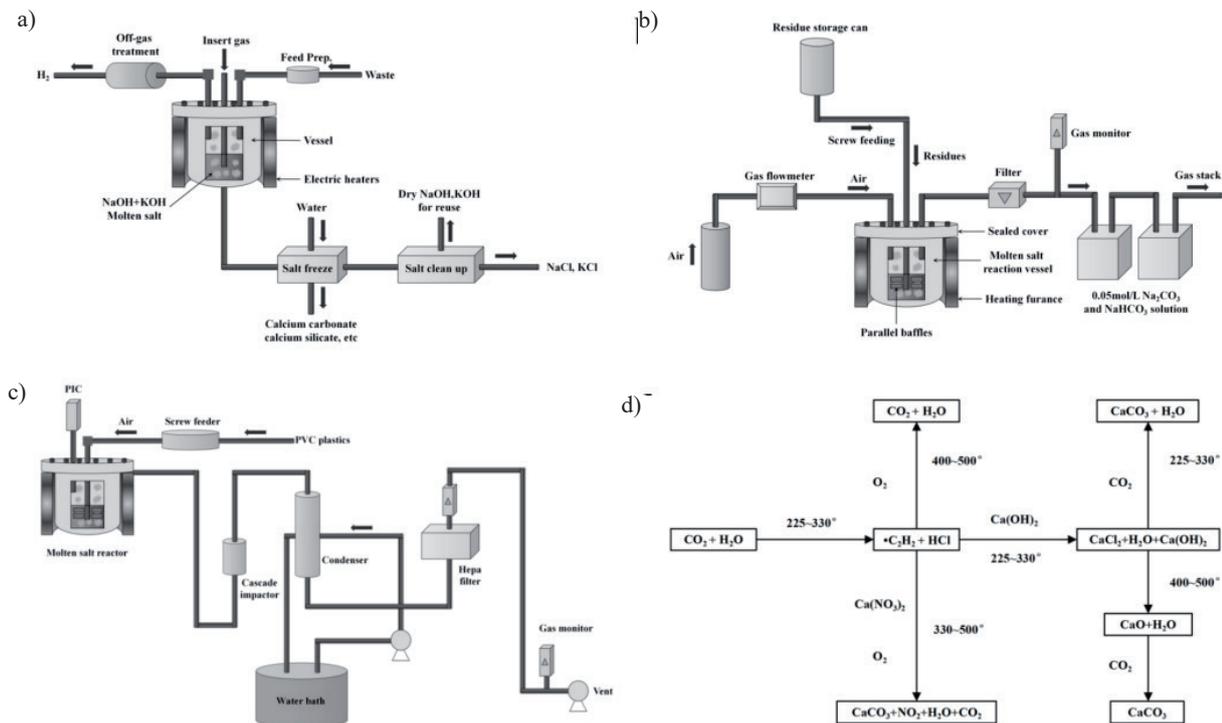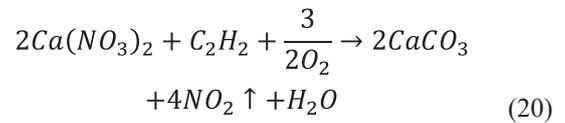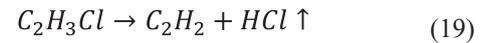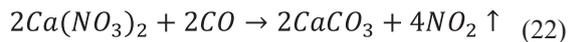$$2Ca(NO_3)_2 + C_2H_2 + \frac{3}{2O_2} \rightarrow 2CaCO_3$$
$$+4NO_2 \uparrow +H_2O \quad (20)$$

Fig. 2. The application of different molten salt systems [104-106, 113, 117].

$$C_2H_2 + 3/2O_2 \rightarrow 2CO + H_2O \qquad (21)$$

$$2Ca(NO_3)_2 + 2CO \rightarrow 2CaCO_3 + 4NO_2 \uparrow \qquad (22)$$

Other Halogen-Containing and Mixing Solid Waste

Fedorov et al. [117] investigated the molten salt treatment of chlorinated organic compounds, including trichloroethylene and chlorobenzene. These compounds were processed in a two-reactor system. In the first reactor, chlorobenzene, carbon tetrachloride, methylene, acetylene, and ethylene were generated, with nearly all organic materials either destroyed or collected in the second reactor. In contrast to the findings of Pandeti et al. [118], Yang et al. observed the presence of chlorine-bearing compounds in the first reactor, likely due to the lower operating temperatures employed in their experiments. Notably, polychlorinated dibenzo-p-dioxins and furans, which are byproducts of incomplete combustion, were not detected in the off-gas system, resulting in a destruction and removal efficiency of approximately 99.99% [119]. Yao et al. presented a treatment method for dichlorodifluoromethane within a molten salt system. Their results indicated that the destruction and removal efficiencies reached 60% when the feed temperature was maintained at 400°C, with no organic compounds detected in the off-gas system. Chlorine and fluorine were effectively captured in the form of sodium chloride and sodium carbonate, eliminating environmental concerns associated with this process. Sugiura et al. [120] explored the use of molten salt systems for treating sewage sludge, highlighting the potential for gasification to serve as fuel for molten carbonate fuel cells. The primary products of this treatment included carbon monoxide and hydrogen.

Upadhye et al. [121] demonstrated that mixed waste can be effectively processed in a molten salt reactor containing sodium, potassium, and bicarbonate. The organic components in the waste are eliminated through a synergistic effect of pyrolysis and oxidation. These mixed wastes often include organic solvents, metals, corrosive substances, and cyanide, as classified by the Resource Conservation and Recovery Act [122, 123]. Due to their high halogen content, these wastes are traditionally managed through incineration. However, molten salt treatment represents a promising alternative, capable of reducing environmental pollution while preserving other valuable materials within the molten salt [121, 124].

The treatment of energetic materials has gained significant attention in light of increasing environmental regulations. Molten salt technology has been employed for the destruction of explosive waste. According to Upadhye et al. [125], the off-gas system showed no traces of hydrocyanic acid or sulfur compounds, indicating that these substances were captured by the alkaline carbonate. Volkovich et al. [126, 127] investigated the treatment of spent nuclear fuel in a molten salt system.

During this process, uranium dioxide is oxidized to diuranate, while fission products dissolve in molten carbonate and subsequently precipitate as insoluble phosphates. Most halogens remain fixed within the molten salt, and fission products precipitate from chlorides.

Economic Considerations and Efficiency

This study provides a qualitative and semi-quantitative comparison of various molten salt systems in terms of energy consumption, treatment efficiency, and economic recovery. Based on literature and existing demonstration plant data, the energy consumption of NaOH-KOH systems is estimated at approximately 1.8-2.2 GJ/t (assuming a system thermal efficiency of ~70%), whereas ternary carbonate systems (Li_2CO_3-Na_2CO_3-K_2CO_3), due to higher operating temperatures and heat capacities, consume about 2.5-3.0 GJ/t. In terms of treatment performance, multiple studies indicate that under reasonable operating conditions, the destruction and removal efficiency (DRE) of molten salt systems often exceeds 99.9%, and hydrogen halides (HCl/HBr) can be captured with efficiencies above 99.9%, significantly reducing the burden on off-gas treatment systems and suppressing PCDD/F formation. The lifecycle cost becomes comparable to incineration when salt reuse exceeds 80%. The comparison of energy consumption and economic performance among different treatment technologies is shown in Table 3 [54, 93, 100, 113, 119].

Based on literature [100] and experimental data, when copper and silver recovery rates reach 90% and 85%, respectively, and waste salt reuse exceeds 80%, the overall treatment cost of the molten salt process can be reduced to approximately 1,200 CNY/t, lower than the average operating cost of typical incineration systems (~1,800 CNY/t). In addition, molten salt systems offer significant economic advantages in pollution control: dioxin emissions can be maintained below 0.01 ng TEQ/Nm³, well below the EU limit of 0.1 ng TEQ/Nm³, substantially reducing both capital and operational costs for off-gas treatment. Overall, molten salt technology outperforms conventional methods in energy efficiency, environmental performance, and resource recovery. Its economic competitiveness primarily depends on the efficiency of the salt circulation system and the value of recovered metals. Further reductions in salt regeneration energy consumption and improvements in recovery rates could make molten salt processing one of the most cost-effective options for halogen-containing solid waste treatment [54, 93].

Literature analysis shows that increasing the waste salt circulation rate from 70% to 90% can reduce the overall treatment cost by approximately 15%. Economically, although the initial investment for molten salt systems-including reactors, corrosion-resistant materials, and salt recovery units-is generally higher than for conventional incineration, long-term operation

Table 3. Comparison of energy consumption and economic performance among different treatment technologies.

Technology Type	Energy Consumption (GJ/t)	Initial investment (10⁴ CNY /100 t·d unit)	Operating cost (CNY/t)	DRE (%)	Halogen capture efficiency (%)	Metal recovery potential	Dioxin emission (ng TEQ/Nm³)	Remarks
Conventional incineration	3.0-3.5	800-1000	1800-2200	98-99	60-70	Low	0.10-0.50	High cost of flue-gas purification
Pyrolysis	2.2-2.8	900-1100	1500-1900	98-99.5	75-85	Medium	0.05-0.15	Lower energy use, incomplete dehalogenation
Molten-salt (NaOH-KOH)	1.8-2.2	1100-1300	1200-1500	99.99	>99.9	High	<0.01	Complete halogen fixation, recyclable salt
Molten-salt (Li_2CO_3-Na_2CO_3-K_2CO_3)	2.5-3.0	1200-1500	1300-1600	99.99	>99.9	High	<0.01	Excellent thermal stability, suitable for mixed wastes
Molten-salt ($Ca(NO_3)_2$-$NaNO_3$)	2.0-2.4	900-1200	1400-1600	98-99	95-98	Medium	0.03-0.05	Operates at low temperature, risk of nitrate decomposition

Note: 1. Data are compiled from References [54, 93, 100, 113, 119] and representative pilot-scale projects (assuming system thermal efficiency of ≈70%). 2. All cost data are expressed in Chinese Yuan (CNY); energy consumption is per ton of waste treated. 3. "DRE" = Destruction and Removal Efficiency. 4. The listed values represent typical ranges and relative trends rather than absolute design parameters.

can yield three types of economic benefits: (1) reduced costs for off-gas and ash disposal, (2) additional revenue from recoverable metals and salts, and (3) savings in indirect costs through lower environmental compliance expenses and avoided penalties. Considering these factors, under medium- to long-term operation, the unit treatment cost of molten salt systems can in some cases approach or even outperform conventional processes, depending on feed composition, recovery rates, and salt regeneration efficiency. It should be noted that several numerical estimates in this study are derived from reports at different experimental or demonstration scales, introducing uncertainties due to process scale and feed composition variations [100, 103, 104, 113].

Comparisons and Technological Perspectives

To comprehensively evaluate treatment routes for halogen-containing solid waste, this study compares key indicators of incineration, pyrolysis, plasma, and molten salt technologies in terms of environmental performance, energy consumption, economic feasibility, and resource recovery, as shown in Table 4. The carbonate composite system combines high thermal stability with strong halogen absorption capability, enabling near-zero pollutant emissions and effective salt recycling. By contrast, incineration is mature but incurs high off-gas treatment costs, pyrolysis suffers from incomplete halogen removal, and plasma technology, while thorough, is limited by high energy consumption and investment. From an integrated environmental-economic-engineering perspective, the composite molten salt synergistic system represents a more promising green treatment route for halogen-containing wastes.

This study proposes a multi-criteria evaluation approach to systematically analyze mainstream molten salt systems. The evaluation indicators include: (1) technical performance, such as destruction and removal efficiency of organic compounds, hydrogen halide/ halogen absorption efficiency, and suppression of dioxin/ furan formation. (2) environmental metrics, including emissions of NOx, SOx, volatile heavy metals, and persistent organic pollutants in off-gases. (3) economic feasibility, encompassing unit treatment costs and potential revenues from recovered metals and salts. (4) operation and maintenance considerations, including system complexity, corrosion resistance requirements, and waste salt management difficulty. (5) scalability and applicability, namely the suitability for mixed wastes and large-scale industrial implementation. Quantitative indicator values are primarily drawn from literature and reasonable estimates based on experimental or demonstration data. According to the Basel Convention and the EU Directive on the Incineration of Hazardous Waste (2000/76/EC), dioxin emissions must not exceed 0.1 ng TEQ/Nm³, and the cross-border illegal transfer of halogenated waste is prohibited [128]. In China, the Solid Waste Pollution Prevention and Control Law

Table 4. Comprehensive comparison of major disposal technologies for halogenated solid wastes.

Technology	Energy consumption level	Halogen fixation efficiency	Dioxin suppression performance	Resource recovery potential	Economic feasibility	Industrial maturity	Overall score
Incineration	High	Moderate (60-70%)	Moderate	Low	Medium	High	0.65
Pyrolysis	Medium	Relatively high (75-85%)	Good	Medium	Medium-low	Medium	0.72
Plasma treatment	Very high	Very high (>99%)	Excellent	Medium	Low	Low	0.68
Molten salt (Li_2CO_3-Na_2CO_3-K_2CO_3)	Medium	Extremely high (>99.9%)	Excellent	High	High	Medium-high	0.89

Note: 1. Evaluation criteria include four weighted dimensions: energy consumption (0.25), environmental performance (0.25), economic feasibility (0.25), and engineering applicability (0.15). 2. The "Overall score" represents the weighted normalized performance index of each technology based on literature data and pilot-scale studies. 3. "Dioxin suppression performance" refers to the relative capacity to inhibit the formation of dioxins and related persistent organic pollutants. 4. Data are compiled from representative studies and demonstration reports [54, 93, 100, 113].

requires a hazardous waste harmlessness rate of ≥90%, therefore molten salt technology is a promising and environmentally friendly technology.

The following key conclusions can be drawn: (1) The Li_2CO_3-Na_2CO_3-K_2CO_3 ternary carbonate system exhibits the best performance in organic compound destruction (DRE) and halogen fixation at high temperatures, with literature-reported DRE up to 99.99% and hydrogen halide capture exceeding 99.9%. This makes it particularly advantageous for treating electronic waste and mixed wastes containing multiple halogens. (2) The low-melting-point NaOH-KOH system, operating at relatively lower temperatures (~350ºC) and requiring simpler equipment, demonstrates lower energy consumption and initial investment, making it suitable for small- to medium-scale facilities or sites with investment constraints. (3) The $Ca(NO_3)_2$-$NaNO_3$ nitrate system exhibits oxidation activity even at low temperatures, offering advantages in the pyrolysis/oxidation of PVC and other high-chlorine polymers. However, nitrate salts tend to decompose at high temperatures and have limited thermal stability, restricting their feasibility for long-term continuous operation. (4) For applications requiring the highest environmental cleanliness and where investment is not constrained, the ternary carbonate system is preferred. For scenarios with limited initial investment or requiring lower operating temperatures, the NaOH-KOH system is recommended, coupled with mature salt recovery and corrosion control measures. The NaOH-KOH system can be reused 10-15 cycles under closed-loop conditions while maintaining over 90% performance, whereas the Li_2CO_3-Na_2CO_3-K_2CO_3 system remains stable for approximately 8-12 continuous cycles. The economic threshold occurs when the salt regeneration rate falls below 70%, beyond which the overall process cost increases significantly. This comparison provides clear guidance for engineering selection and highlights critical areas for further research, such as waste salt regeneration, material corrosion resistance, and quantitative studies of multiphase heat and mass transfer behavior.

Conclusions

Molten salt technology demonstrates significant environmental and economic potential in the treatment of halogen-containing solid wastes. It can efficiently degrade organic components, immobilize halogens, and recover valuable metals, while markedly reducing emissions of dioxins and nitrogen oxides. Through a systematic comparison of alkaline, carbonate, nitrate, and composite molten salt systems, this study confirms that the ternary carbonate system offers the greatest advantages in high-temperature stability and pollutant control, making it suitable for electronic waste and mixed waste streams; the NaOH-KOH system,

with its lower operating temperature, is better suited for small- to medium-scale applications; while the nitrate system exhibits strong oxidative activity, its thermal stability requires improvement. The multi-criteria evaluation framework reveals that the economic competitiveness of molten salt technology depends on the salt recycling rate (>80%) and metal recovery efficiency (Cu/Ag>90%), with unit treatment costs potentially lower than those of conventional incineration (approximately 1200 RMB/ton). Compared with incineration, pyrolysis, and plasma technologies, the molten salt process shows superior integrated environmental, economic, and engineering performance, aligning with global environmental regulations and circular economy principles. The current optimal approach for halogen-containing waste management involves a recommended treatment route of "mixed waste → molten salt co-pyrolysis → halogen fixation → metal recovery → waste salt regeneration and recycling".

This study provides guidance based on literature data and future research should focus on: (1) developing catalytically doped, low-corrosion composite molten salts to enhance organic oxidation rates, (2) exploring multiphase flow and heat transfer behavior through CFD numerical simulation and machine learning-based thermodynamic prediction, (3) integrating carbon reduction and energy recovery technologies for synergistic optimization, (4) establishing standardized policy frameworks for waste salt regeneration and metal separation. These directions will further enhance the engineering potential of molten salt technology, promote its transition from laboratory research to industrial application, and ultimately contribute to sustainable hazardous waste management.

Acknowledgments

Conflict of Interest

The authors declare no conflict of interest.

References

1. LIN R., AMRUTE A.P., PEREZ-RAMIREZ J. Halogen-mediated conversion of hydrocarbons to commodities. Chemical Reviews. **117** (5), 4182, **2017**.

2. JESCHKE P. Latest generation of halogen-containing pesticides. Pest Management Science. **73** (6), 1053, **2017**.

3. JESCHKE P. The unique role of halogen substituents in the design of modern agrochemicals. Pest Management Science: formerly Pesticide Science. **66** (1), 10, **2010**.

4. SABET M. Advancements in halogen-free polymers: Exploring flame retardancy, mechanical properties, sustainability, and applications. Polymer-Plastics Technology and Materials. **63** (13), 1794, **2024**.

5. IKE-EZE I., UCHEJI O., UBI P., OJI E., AIGBODION V., OMAH A., OGBUEFI C. An Overview of Flame Retardants in Printed Circuit Boards for LEDs and other Electronic Devices. Journal of Materials and Environmental Science. **14** (4), 410, **2023**.

6. JANDRIC A., PART F., FINK N., COCCO V., MOUILLARD F., HUBER-HUMER M., SALHOFER S., ZAFIU C. Investigation of the heterogeneity of bromine in plastic components as an indicator for brominated flame retardants in waste electrical and electronic equipment with regard to recyclability. Journal of Hazardous Materials. **390**, 121899, **2020**.

7. ZHANG Z., MALIK M.Z., KHAN A., ALI N., MALIK S., BILAL M. Environmental impacts of hazardous waste, and management strategies to reconcile circular economy and eco-sustainability. Science of The Total Environment. **807**, 150856, **2022**.

8. CHAABAN M.A. Hazardous waste source reduction in materials and processing technologies. Journal of Materials Processing Technology. **119** (1-3), 336, **2001**.

9. ZHAO T., MAHANDRA H., MARTHI R., JI X., ZHAO W., CHAE S., TRAVERSY M., LI W., YU F., LI L. An overview on the life cycle of lithium iron phosphate: synthesis, modification, application, and recycling. Chemical Engineering Journal. 149923, **2024**.

10. YANG Z., HUANG H., LIN F. Sustainable electric vehicle batteries for a sustainable world: perspectives on battery cathodes, environment, supply chain, manufacturing, life cycle, and policy. Advanced Energy Materials. **12** (26), 2200383, **2022**.

11. JAN W., KHAN A.D., IFTIKHAR F.J., ALI G. Recent advancements and challenges in deploying lithium sulfur batteries as economical energy storage devices. Journal of Energy Storage. **72**, 108559, **2023**.

12. CENCI M.P., SCARAZZATO T., MUNCHEN D.D., DARTORA P.C., VEIT H.M., BERNARDES A.M., DIAS P.R. Eco-friendly electronics – a comprehensive review. Advanced Materials Technologies. **7** (2), 2001263, **2022**.

13. KUMAR P., SINGH S., GACEM A., YADAV K.K., BHUTTO J.K., ALRESHIDI M.A., KUMAR M., KUMAR A., YADAV V.K., SONI S. A review on e-waste contamination, toxicity, and sustainable clean-up approaches for its management. Toxicology. 153904, **2024**.

14. FAZARI J., HOSSAIN M.Z., CHARPENTIER P. A review on metal extraction from waste printed circuit boards (wPCBs). Journal of Materials Science. **59** (27), 12257, **2024**.

15. ALABI O.A., PASA T.B.C., ADEBO T.C. Environmental contamination and public health effects of household hazardous waste. Journal of Biomedical Research & Environmental Sciences. **4** (9), 1323, **2023**.

16. 1LEBELO K., MALEBO N., MOCHANE M.J., MASINDE M. Chemical contamination pathways and the food safety implications along the various stages of food production: a review. International Journal of Environmental Research and Public Health. **18** (11), 5795, **2021**.

17. LEWANDOWSKI K., SKÓRCZEWSKA K. A brief review of poly (vinyl chloride) (PVC) recycling. Polymers. **14** (15), 3035, **2022**.

18. AKOVALI G. Plastic materials: polyvinyl chloride (PVC). In: Toxicity of building materials, Elsevier: pp. 23, **2012**.

19. RAMESH S., WINIE T., AROF A. Investigation of mechanical properties of polyvinyl chloride–polyethylene oxide (PVC–PEO) based polymer electrolytes for lithium polymer cells. European Polymer Journal. **43** (5), 1963, **2007**.

20. TITOW W.V. PVC plastics: properties, processing, and applications. Springer Science & Business Media, **2012**.

21. KHAN S.M., GULL N., KHAN R.U., BUTT M.T.Z. Polyvinylchloride (PVC): structure and properties relationship. Polyvinylchloride-based Blends: Preparation, Characterization and Applications. 19, **2022**.

22. DONG J., TIAN X., SUN X.-Y., JIANG W.-W., LUO Q., YANG Q. Study on synthesis technology of 4, 6-dinitro-l, 2, 3-trichlorobenzene and waste acid recyling. Procedia Engineering. **18** 381, **2011**.

23. MARTIN E.T., MCGUIRE C.M., MUBARAK M.S., PETERS D.G. Electroreductive remediation of halogenated environmental pollutants. Chemical Reviews. **116** (24), 15198, **2016**.

24. ZHONG Y., PENG P.A., YU Z., DENG H. Effects of metals on the transformation of hexabromocyclododecane (HBCD) in solvents: Implications for solvent-based recycling of brominated flame retardants. Chemosphere. **81** (1), 72, **2010**.

25. TRIEBERT D., HANEL H., BUNDT M., WOHNIG K. Solvent-based recycling. In: Circular Economy of Polymers: Topics in Recycling Technologies, ACS Publications: pp.33, **2021**.

26. MEHTA P., KUMARASWAMY A., SARASWAT V., PRAVEENKUMAR B. Recycling of waste propellant and the challenges in disposal: range safety. 2nd International Conference on Range Technology (ICORT), Chandipur, Balasore, India, **2021**.

27. MORGAN M.E., MILLER P.L. Recycling propellants and explosives into the commercial explosive industry. International Journal of Energetic Materials and Chemical Propulsion. **4** (1-6), **1997**.

28. MARANDA A., WACHOWSKI L., KUKFISZ B., MARKOWSKA D., PASZULA J. Valorization of Energetic Materials from Obsolete Military Ammunition Through Life Cycle Assessment (LCA): A Circular Economy Approach to Environmental Impact Reduction. Sustainability. **17** (1), 346, **2025**.

29. TALAWAR M., SIVABALAN R., MUKUNDAN T., MUTHURAJAN H., SIKDER A., GANDHE B., RAO A.S. Environmentally compatible next generation green energetic materials (GEMs). Journal of Hazardous Materials. **161** (2-3), 589, **2009**.

30. STEWART M. Removal of organic and inorganic contaminants from oil sands tailings using carbon based adsorbents and native sediment. University of Alberta (Canada), **2013**.

31. GRIFFITHS T.R., VOLKOVICH V.A. A new technology for the nuclear industry for the complete and continuous pyrochemical reprocessing of spent nuclear fuel: catalyst enhanced molten salt oxidation. Nuclear Technology. **163** (3), 382, **2008**.

32. KUMAR S., CHIEMCHAISRI C., MUDHOO A. Bioreactor landfill technology in municipal solid waste treatment: An overview. Critical Reviews in Biotechnology. **31** (1), 77, **2011**.

33. HAMER G. Solid waste treatment and disposal: effects on public health and environmental safety. Biotechnology Advances. **22** (1-2), 71, **2003**.

34. RABL A., SPADARO J.V., ZOUGHAIB A. Environmental impacts and costs of solid waste: a comparison of landfill and incineration. Waste Management & Research. **26** (2), 147, **2008**.

35. BOLYARD S.C., REINHART D.R. Application of landfill treatment approaches for stabilization of municipal solid waste. Waste management. **55**, 22, **2016**.

36. NIE Y. Development and prospects of municipal solid waste (MSW) incineration in China. Frontiers of Environmental Science & Engineering in China. **2**, 1, **2008**.

37. HJELMAR O. Disposal strategies for municipal solid waste incineration residues. Journal of Hazardous Materials. **47** (1-3), 345, **1996**.

38. MA C., KUMAGAI S., SAITO Y., YOSHIOKA T., HUANG X., SHAO Y., RAN J., SUN L. Recent advancements in pyrolysis of halogen-containing plastics for resource recovery and halogen upcycling: a state-of-the-art review. Environmental Science & Technology. **58** (3), 1423, **2024**.

39. LIN C., YANG T., CHEN S., LI M., WANG S., HUANG Q. Characteristics of Molten Salt Gasification of Waste PVC. Processes. **12** (2), 306, **2024**.

40. MARTÍNEZ-NARRO G., HASSAN S., PHAN A.N. Chemical recycling of plastic waste for sustainable polymer manufacturing-A critical review. Journal of Environmental Chemical Engineering. 112323, **2024**.

41. DENG J., YI B., MAŠEK O., YUAN X., HWANG S.Y., ONG H.C., HUA Z., OK Y.S. Co-pyrolysis of biomass and plastic waste into carbon materials with environmental applications: a critical review. Green Chemistry. **2025**.

42. FARAJI F., GOLMOHAMMADZADEH R., PICKLES C.A. Potential and current practices of recycling waste printed circuit boards: a review of the recent progress in pyrometallurgy. Journal of Environmental Management. **316** 115242, **2022**.

43. UDAYAKUMAR S., ABD RAZAK M.I.B., ISMAIL S. Recovering valuable metals from Waste Printed Circuit Boards (WPCB): A short review. Materials Today: Proceedings. **66**, 3062, **2022**.

44. NIE C.-C., LI X.-G., SUN Q.-Y., GAO Q., ZHU X.-N., LYU X.-J., LI L., YOU X.-F. Clean and efficient process for the recycling of all components from waste printed circuit boards: Pre-treatment, bio-metallurgy, and deep utilization. Journal of Cleaner Production. 142810, **2024**.

45. THEMBA N., SIBALI L.L., CHOKWE T.B. A review on the formation and remediations of polychlorinated dibenzo p-dioxins and dibenzo-furans (PCDD/Fs) during thermal processes with a focus on MSW process. Air Quality, Atmosphere & Health. **16** (10), 2115, **2023**.

46. LIN S.-L., WU J.-L., CHEN W.-H., WU H., TANG W. Ultra-low PCDD/F emissions and their particle size and mass distribution in a hazardous waste treatment system. Journal of Hazardous Materials. **423**, 127032, **2022**.

47. GAO C.Q., LONG J., YUE Y., LI B., HUANG Y., WANG Y., ZHANG J., ZHANG L., QIAN G. Degradation and regeneration inhibition of PCDD/Fs in incineration fly ash by low-temperature thermal technology. Journal of Hazardous Materials. 135315, **2024**.

48. MATHEW N., SOMANATHAN A., TIRPUDE A., PILLAI A.M., MONDAL P., ARFIN T. Dioxins and their impact: a review of toxicity, persistence, and novel remediation strategies. Analytical Methods. **2025**.

49. PIETRELLI L., FERRO S., VOCCIANTE M. Eco-friendly and cost-effective strategies for metals recovery from printed circuit boards. Renewable and Sustainable Energy Reviews. **112**, 317, **2019**.

50. YUAN Z., LIU H., YONG W.F., SHE Q., ESTEBAN J. Status and advances of deep eutectic solvents for metal separation and recovery. Green Chemistry. **24** (5), 1895, **2022**.

51. HAMIDINEJAD M., ZHAO B., ZANDIEH A., MOGHIMIAN N., FILLETER T., PARK C.B. Enhanced electrical and electromagnetic interference shielding properties of polymer–graphene nanoplatelet composites fabricated via supercritical-fluid treatment and physical foaming. ACS Applied Materials & Interfaces. **10** (36), 30752, **2018**.

52. LI K., XU Z. A review of current progress of supercritical fluid technologies for e-waste treatment. Journal of Cleaner Production. **227**, 794, **2019**.

53. PERRUT M. Supercritical fluid applications: Industrial developments and economic issues. Industrial & Engineering Chemistry Research. **39** (12), 4531, **2000**.

54. YAO Z., LI J., ZHAO X. Molten salt oxidation: A versatile and promising technology for the destruction of organic-containing wastes. Chemosphere. **84** (9), 1167, **2011**.

55. LIN C., CHI Y., JIN Y., JIANG X., BUEKENS A., ZHANG Q., CHEN J. Molten salt oxidation of organic hazardous waste with high salt content. Waste Management & Research. **36** (2), 140, **2018**.

56. LANTELME F., GROULT H. Molten salts chemistry: from lab to applications. Elsevier, **2013**.

57. LOVERING D., OBLATH R. Water in molten salts: Industrial and electrochemical consequences. In Ionic Liquids, Springer: pp.165, **1981**.

58. NUNES V., QUEIRÓS C., LOURENÇO M., SANTOS F., DE CASTRO C.N. Molten salts as engineering fluids-A review: Part I. Molten alkali nitrates. Applied Energy. **183**, 603, **2016**.

59. SHANG H., LU Y., ZHAO F., CHAO C., ZHANG B., ZHANG H. Preparing high surface area porous carbon from biomass by carbonization in a molten salt medium. RSC Advances. **5** (92), 75728, **2015**.

60. KAMALI A.R., YANG J. Effect of molten salts on the structure, morphology and electrical conductivity of PET-derived carbon nanostructures. Polymer Degradation and Stability. **177**, 109184, **2020**.

61. LIU B., ZHANG L., ZHOU K., LI Z., WANG H. Electrical conductivity and molten salt corrosion behavior of spinel nickel ferrite. Solid State Sciences. **13** (8), 1483, **2011**.

62. CORNWELL K. The thermal conductivity of molten salts. Journal of Physics D: Applied Physics. **4** (3), 441, **1971**.

63. LAGERAAEN P., KALB P., GRIMMETT D., GAY R., NEWMAN C. Polyethylene encapsulation of molten salt oxidation mixed low-level radioactive salt residues. Brookhaven National Lab., **1995**.

64. NUNES V., LOURENÇO M., SANTOS F., DE CASTRO C.N. Molten alkali carbonates as alternative engineering fluids for high temperature applications. Applied Energy. **242**, 1626, **2019**.

65. RUDOLPH J., HAAS P., BELL J., CROSLEY S., CALHOUN JR C., GORIN A., NULF L. Molten salt oxidation of chloro-organic compounds: Experimental results for product gas compositions and final forms studies. Oak Ridge National Lab. (ORNL), Oak Ridge, TN (United States), **1995**.

66. ABBEY L., MCDOWELL M., DARNELL A., GAY R., KNUDSEN K., NEWMAN C. Final report for molten salt oxidation of RMDF mixed wastes. Rockwell International, California. **1993**.

67. ADAMSON M.G., CHIBA Z., VON HOLTZ E.H., STREIT R.D. Development of advanced waste treatment technologies for demonstration in the Mixed Waste Management Facility. Radioactive Waste Processing. **1995**.

68. COOLEY C. Status review of molten salt oxidation for mixed low-level waste, EM-50, Memorandum. Dep. Energy, US Government. **17 1998**.

69. GRIFFITHS T.R., VOLKOVICH V.A., ANGHEL E.M., CARPER W.R. Molten salt oxidation for the efficient destruction of radioactive, Hazardous Chemical, Medical Waste and Munitions, 24th International Conference on Incineration and Thermal Treatment Technologies, Galveston, Texas, **2005**.

70. FRAY D.J. Emerging molten salt technologies for metals production. JOM: the Journal of the Minerals, Metals & Materials Society. **53** (10), 27, **2001**.

71. XIAO M., LUO B., KONAROVA M., WANG Z., WANG L. Molten salt synthesis of atomic heterogeneous catalysts: old chemistry for advanced materials. European Journal of Inorganic Chemistry. **2020** (31), 2942, **2020**.

72. SUZUKI R.O., ISHIKAWA M., ONO K. $NbSi_2$ coating on niobium using molten salt. Journal of Alloys and Compounds. **336** (1-2), 280, **2002**.

73. FU J., HOU Y., LIU X., ZHENG M., ZHU M. A construction strategy of ferroelectrics by the molten salt method and its application in the energy field. Journal of Materials Chemistry C. **8** (26), 8704, **2020**.

74. WANG S., RINEISKI A., MASCHEK W. Molten salt related extensions of the SIMMER-III code and its application for a burner reactor. Nuclear Engineering and Design. **236** (14-16), 1580, **2006**.

75. YIN H., LU B., XU Y., TANG D., MAO X., XIAO W., WANG D., ALSHAWABKEH A.N. Harvesting capacitive carbon by carbonization of waste biomass in molten salts. Environmental Science & Technology. **48** (14), 8101, **2014**.

76. JANZ G.J., PERANO J.L. High-temperature heat content and fusion properties for binary carbonate mixtures: Li_2CO_3, K_2CO_3 and Na_2CO_3. Transactions of the Faraday Society. **60**, 1742, **1964**.

77. SHETH A.C., SASTRY C., YEBOAH Y.D., XU Y., AGARWAL P. Catalytic gasification of coal using eutectic salts: recovery, regeneration, and recycle of spent eutectic catalysts. Journal of the Air & Waste Management Association. **53** (4), 451, **2003**.

78. ANDERSON A. Investigation of the carbochlorination process for the conversion of rare earth oxides into chlorides and measurement of their solubility in inert molten salts. Colorado School of Mines, **2015**.

79. YAO Z., XIAO J., MAO Q., WANG G., TANG L., YOU Z., ZHONG Q. Detoxification and recovery of spent carbon cathodes via $NaOH–Na_2CO_3$ binary molten salt roasting–water leaching: toward a circular economy for hazardous solid waste from aluminum electrolysis. ACS Sustainable Chemistry & Engineering. **8** (45), 16912, **2020**.

80. ALDEN N., HUMERICK Z., TEIXEIRA A., DITTAMI J.P., DATTA R. Molten salt gasification of biomass. Worcester Polytechnic Institute. **2009**.

81. TAKEDA O., AOKI D., YOKKA Y., YAMAMURA T., SATO Y. Decomposition of mono-, di-and tri-chlorobenzene by using basic molten salts. ISIJ International. **52** (9), 1705, **2012**.

82. YE L., OUYANG Z., CHEN Y., LIU S. Recovery of rhenium from tungsten-rhenium wire by alkali fusion in

KOH-K_2CO_3 binary molten salt. International Journal of Refractory Metals and Hard Materials. **87**, 105148, **2020**.

83. NISHIKATA A., HARUYAMA S. Electrochemical monitoring of the corrosion of Ni, Fe, and their alloys in molten salts. Corrosion. **42** (10), 578, **1986**.

84. VOLKOVICH V.A., GRIFFITHS T.R., FRAY D.J., FIELDS M. Oxidation of ceramic uranium dioxide in alkali metal carbonate-based melts: a study using various oxidants and comparison with UO2 powder. Journal of Nuclear Materials. **256** (2-3), 131, **1998**.

85. XIN G., XING Y., SUN W., SONG J., BAO J., AN J., LIU F., SHE S., HU W., BULIN C. Construction of three-dimensional porous graphene with N, S co-doping in KOH-K_2CO_3 eutectic active molten salt system for supercapacitors. Electrochimica Acta. **477**, 143820, **2024**.

86. JI C., YANG X., MA Y., CHI H., XIE J. Molecular dynamics study on thermophysical properties of K_2CO_3 molten salt-based SiO_2 nanofluids using Buckingham potential framework. Journal of Molecular Liquids. **407**, 125231, **2024**.

87. SHE H., LV P., HE X., BAI Y., WANG J., SONG X., SU W., WEI J., YU G. Characteristics of CO_2 gasification reaction and biochar structure evolution of rice straw in K_2CO_3-Na_2CO_3-Li_2CO_3 ternary molten salt. Process Safety and Environmental Protection. **197**, 107051, **2025**.

88. WANG Z., LIU C., OUYANG J., XUE B., XU J., ZHAI J., XIAO R. Porous carbon materials derived from rice husk pyrolysis with $NaCl/Na_2CO_3$ binary molten salt for CO_2 capture. Industrial Crops and Products. **227**, 120808, **2025**.

89. HSU P.C. Integrated demonstration of molten salt oxidation with salt recycle for mixed waste treatment. Lawrence Livermore National Lab. (LLNL), Livermore, CA (United States), **1997**.

90. HSU P.C., HIPPLE D.L., FOSTER K.G., FORD T.D., ADAMSON M.G. Molten salt oxidation for treating low-level mixed wastes. Waste Treatment. **99**, **1999**.

91. ADAMSON M., BRUMMOND W., HIPPLE D., HSU P., SUMMERS L., VON HOLTZ E., WANG F. MSO spent salt clean-up recovery process. Lawrence Livermore National Laboratory (LLNL), Livermore, CA (United States), **1997**.

92. LV Y., WANG Y., ZHANG D., WU C., ZHANG J., ZHAO Z., NABI M., LUO X., XIAO K. A Mini-Review on Safe Treatment and Valorization of Salt Waste in Chemical Production Processes in China. Water. **16** (11), 1620, **2024**.

93. DE FIGUEIREDO LUIZ D., BOON J., RODRIGUEZ G.O., VAN SINT ANNALAND M. Review of the molten salt technology and assessment of its potential to achieve an energy efficient heat management in a decarbonized chemical industry. Chemical Engineering Journal. 155819, **2024**.

94. EDWARDS B.H., PAULLIN J.N., COGHLAN-JORDAN K. Emerging technologies for the control of hazardous wastes. Journal of Hazardous Materials. **12** (2), 201, **1985**.

95. ADAMSON M., FORD T., FOSTER K., HIPPLE D., HOPPER R., HSU P. Molten salt oxidation for treating low-level mixed wastes. Lawrence Livermore National Lab. (LLNL), Livermore, CA (United States), **1998**.

96. NORAIZAN A.N.B.M., ABDULLAH N.F.B., ABIDIN M.L.Q.A.-W.B.Z., GUO A.C.W., MUBARAK N.M., KARRI R.R. Insight mechanism of rice husk as renewable energy for bio-oil production. Biomass Conversion and Biorefinery. 1, **2024**.

97. XIAO X., SUN K., MA J., ZHOU S., WANG J., LI Y., WANG S., DENG Q. Recording thermal history of pork meat by self-coloration gel. Journal of Food Engineering. **381**, 112193, **2024**.

98. KLEIN A. Gasification: an alternative process for energy recovery and disposal of municipal solid wastes. Columbia University. **2002**, 1, **2002**.

99. WANG X.-Z., ZHENG Y.-H., XUE Y., YAN Y.-D., MA F.-Q., ZHANG M.-L., BAI H.-Y., KOU Z.-Q., LIU J.-P. Study on the destruction process of cationic exchange resins treated by Li_2CO_3-Na_2CO_3-K_2CO_3 molten salt. Journal Of Environmental Chemical Engineering. **9** (5), 105948, **2021**.

100. COOPER J.F., BRUMMOND W., CELESTE J., FARMER J., HOENIG C., KRIKORIAN O.H., UPADHYE R., GAY R.L., STEWART A., YOSIM S. Molten salt processing of mixed wastes with offgas condensation. Lawrence Livermore National Lab., CA (USA), **1991**.

101. VAN SETTEN B., VAN GULIJK C., MAKKEE M., MOULIJN J. Molten salts are promising catalysts. How to apply in practice? Topics in Catalysis. **16**, 275, **2001**.

102. STELMAN D., GAY R. Fundamental chemical and process differences between molten salt oxidation and incineration. Report for Rockwell International, Canoga Park, CA. **1993**.

103. GRIFFITHS T.R., VOLKOVICH V.A., ANGHEL E.M. Molten salt oxidation: a reassessment of its supposed catalytic mechanism and hence its development for the disposal of waste automotive tires. ECS Proceedings Volumes. **2002** (1), 306, **2002**.

104. FLANDINET L., EDJAR F., GHETTA V., FOULETIER J. Metals recovering from waste printed circuit boards (WPCBs) using molten salts. Journal of Hazardous Materials. **213-214**, 485, **2012**.

105. WANG J., CHEN Z., DU H. NaOH-KOH Capillary Action Enhances the Pyrolysis and Debromination of Waste Printed Circuit Boards. ACS Sustainable Chemistry & Engineering. (50), 9, **2021**.

106. LIN C., CHI Y., JIN Y. Experimental Study on Treating Waste Printed Circuit Boards by Molten Salt Oxidation. Waste & Biomass Valorization. **8** (7), 2523, **2017**.

107. FEI L.I., ZENGLI Z., HAIBIN L.I., YONG C. Study on gasification characteristics of waste printed circuit boards (PCB) in molten salts: II Gasification reaction kinetics model[J]. Acta Scientiae Circumstantiae, **28** (6), 1161, **2008**.

108. ARUN K.J., MEENA M. Application of PVC-A superior material in the fields of Science and Technology. Polymer-Plastics Technology and Materials. **63** (15), 20, **2024**.

109. YE L., QI C., HONG J., MA X. Life cycle assessment of polyvinyl chloride production and its recyclability in China. Journal of Cleaner Production. **142**, 2965, **2017**.

110. TAHIRA B.E., KHAN M.I., SAEED R., AKHWAN S. A Review- Thermal Degradation and Stabilization of Poly (Vinyl Chloride). International Journal of Research. **1**, 732, **2014**.

111. JURAEV I., MUKHIDDINOV B., JURAEV S., SABIROVA N. Development of polyvinyl chloride compositions with polyphenylene ether and investigation of their properties. AIP Conference Proceedings. **3268** (1), 040035, **2025**.

112. HA T.T., QUY N.H., KY P.Q., LONG N.Q., BAC V.T., NHAN D.D. Study on application of molten salt

oxidation technology (MSO) for PVC wastes treatment. The VAEC - Annual Report for 2006, Viet Nam, **2007**.

113. YANG H.C., CHO Y.J., YUN J.S., KIM J.H. Destruction of halogenated plastics in a molten salt oxidation reactor. The Canadian Journal of Chemical Engineering. **81** (3-4), 713, **2003**.

114. NYGÅRD H.S., OLSEN E. Review of thermal processing of biomass and waste in molten salts for production of renewable fuels and chemicals. International Journal of Low-Carbon Technologies. **7** (4), 318, **2012**.

115. BERTOLINI G.E., FONTAINE J. Value recovery from plastics waste by pyrolysis in molten salts. Conservation & Recycling. **10** (4), 331, **1987**.

116. FEDOROV A., CHEKRYSHKIN Y., GORBUNOV A. Studies of Recycling of Poly (vinyl chloride) in Molten Na, Ca‖NO_3, OH Systems. International Scholarly Research Notices. **2012** (1), 768134, **2012**.

117. FEDOROV A., CHEKRYSHKIN Y.S. Oxidative degradation and pyrolysis of polyvinyl chloride in binary mixtures of the system K, Na, Ca‖NO_3, NO_2, OH. Russian Journal of Applied Chemistry. **83**, 1450, **2010**.

118. PANDETI S., BUCKLEY S. Molten salt oxidation of chlorobenzene. Combustion Science and Technology. **176** (2), 257, **2004**.

119. HSU P.C., HIPPIE D.L., FOSTER K.G., HOPPER R.W., FORD T.D. Organic Waste Processing using Molten Salt Oxidation. Advances in Molten Salts, Begell House, **1998**.

120. SUGIURA K., MINAMI K., YAMAUCHI M., MORIMITSU S., TANIMOTO K. Gasification characteristics of organic waste by molten salt. Journal of Power Sources. **171** (1), 228, **2007**.

121. UPADHYE R., WILDER J., KARLSEN C. Molten salt destruction process for mixed wastes. Lawrence Livermore National Lab., CA (United States), **1993**.

122. GAY R., NAVRATIL J., NEWMAN C. Molten Salt Oxidation of mixed wastes. Proceedings of the 1993 International Conference on Nuclear Waste Management and Environmental Remediation, ASME, **1993**.

123. JIANG G., WANG J., AL-SALEM S.M., LEEKE G.A. Molten solar salt pyrolysis of mixed plastic waste: process simulation and technoeconomic evaluation. Energy & Fuels. **34** (6), 7397, **2020**.

124. BELL J., HAAS P., RUDOLPH J. Molten salt oxidation of mixed wastes: separation of radioactive materials and resource conservation and recovery act (RCRA) materials. Separation Science and Technology. **30** (7-9), 1755, **1995**.

125. UPADHYE R.S., PRUNEDA C.O., WATKINS B.E. Molten salt destruction of energetic material wastes as an alternative to open burning. Chemistry for the Protection of the Environment. **2**, 267, **1996**.

126. VOLKOVICH V.A., GRIFFITHS T.R., FRAY D.J., FIELDS M. Increased oxidation of UO2 in molten alkali-metal carbonate based mixtures by increasing oxygen solubility and by controlled generation of superoxide ions, and evidence for a new sodium uranate. Journal of the Chemical Society, Faraday Transactions. **93** (21), 3819, **1997**.

127. VOLKOVICH V.A., GRIFFITHS T.R., THIED R.C. Treatment of molten salt wastes by phosphate precipitation: removal of fission product elements after pyrochemical reprocessing of spent nuclear fuels in chloride melts. Journal of Nuclear Materials. **323** (1), 49, **2003**.

128. LI X, BERTOS M F, HILLS C D, CAREY P J, SIMON S. Accelerated carbonation of municipal solid waste incineration fly ashes. Waste Management, **27** (9), 1200, **2007**.