*ISSN 1392–1320 MATERIALS SCIENCE (MEDŽIAGOTYRA). Vol. XX, No. X. 2027*

# Research Progress on the Safe Disposal and Comprehensive Utilization of Electrolytic Manganese Slag

**Jing TAN [1, 2, 3] *, Xinghua PENG [1, 2, 3], Guodong LI [1, 2, 3], Dahai YOU [1, 2, 3], Jin ZHANG [1, 2, 3], Li ZHANG [1, 2, 3]**

[1] *Hubei Institute of Metallurgical Geology (Central South Institute of Metallurgical Geology), Yichang 443000, China*
[2] *Mineral Materials and Applied Engineering Technology Research Center of Hubei Province, Yichang 443000, China*
[3] *Yichang Key Laboratory of Comprehensive Utilization of Mineral Resources, Yichang 443000, China*

http://doi.org/10.5755/j02.ms.45152

*Received 28 May 2026; accepted 5 August 2026*

Manganese is an indispensable strategic resource in the steel, chemical, electronics, and new energy sectors. As the primary solid waste generated during the production of electrolytic manganese metal, electrolytic manganese slag accumulates in massive quantities, yet its comprehensive utilization rate remains below 10 %. This slag is rich in characteristic pollutants such as high concentrations of manganese ions ($Mn^{2+}$), ammonia nitrogen ($NH_4^+$-N), and sulfates ($SO_4^{2-}$), posing a severe challenge to the ecological environment. In recent years, technologies for the safe disposal of electrolytic manganese slag have primarily included water washing, high-temperature solidification, and chemical solidification; these methods can effectively reduce its leaching toxicity. In terms of resource recovery, research and applications have expanded into multiple directions, such as the production of construction materials (cement, concrete, unburned bricks, and roadbed materials), the development of agricultural fertilizers, the recovery of valuable elements, and the synthesis of high-value-added products.

*Keywords:* electrolytic manganese slag, harmless treatment, resource recovery, industrial solid waste.

## 1. INTRODUCTION

Manganese is an indispensable strategic resource in the steel, chemical, electronics, and new energy sectors. Globally, 90 % of manganese is used in the steel industry for desulfurization, deoxidation, and alloying, while the remainder is used in battery cathode materials (such as lithium manganese oxide), agricultural fertilizers, and specialty ceramics [1].

Electrolytic manganese slag is the acid leaching residue generated during the production of electrolytic manganese metal from manganese carbonate or manganite ore, and it constitutes the primary solid waste in the electrolytic manganese industry. According to statistics, when approximately 12 % of the manganese nodules are directly leached to produce electrolytic manganese, 1 ton of metallic manganese generates 8 – 12 tons of electrolytic manganese slag; when soft manganese ore is used to produce electrolytic manganese, 1 ton of metallic manganese generates 3 – 5 tons of electrolytic manganese slag. Currently, the disposal of electrolytic manganese slag primarily involves open-air stockpiling, with a comprehensive utilization rate of less than 10 %. As of 2025, China's existing stockpile of electrolytic manganese slag has exceeded 150 million tons, with an annual increase of over 10 million tons [2]. Safe stockpiling is merely a stopgap measure for the disposal of electrolytic manganese slag; resource recovery is the fundamental solution. However, existing electrolytic manganese slag is difficult to recycle, and newly generated slag cannot be fully absorbed, resulting in the pollution issue caused by electrolytic manganese slag remaining unresolved and severely hindering the green and sustainable development of the electrolytic manganese industry. Therefore, in-depth research on the harmless treatment and resource recovery of electrolytic manganese slag is urgently needed. This study summarizes the current state of research on the harmless treatment and resource utilization of electrolytic manganese slag in recent years, analyzes existing processes and research, and proposes subsequent resource utilization technologies for electrolytic manganese slag.

## 2. ELECTROLYTIC MANGANESE SLAG

### 2.1. Chemical properties of electrolytic manganese slag

Electrolytic manganese slag is a filtered acid slag produced during the manufacturing of metallic manganese. It contains more than ten major elements, including N, P, O, S, and Mn, and its primary mineral components include $SO_3$, $SiO_2$, CaO, and MgO. The main phases present include gypsum ($CaSO_4 \cdot 2H_2O$), quartz ($SiO_2$), and phyllosilicate ($Al_2Si_4O_{10}(OH)_2$). Electrolytic manganese slag is a black, powdery aggregate with a certain degree of stickiness, typically containing 23 % – 36 % moisture [3]. Due to the low grade of manganese ore in China, the production of 1 ton of electrolytic manganese generates 7 ~ 11 tons of electrolytic manganese slag. After prolonged storage, the slag cements into lumps. Furthermore, electrolytic manganese slag is toxic; leaching toxicity tests indicate that its primary characteristic pollutants are manganese ions

* Corresponding author: J. Tan
E-mail: *tanjing0809@alu.scu.edu.cn*

($Mn^{2+}$), ammonia nitrogen ($NH_4^+$-N), and sulfate ($SO_4^{2-}$), which pose significant hazards to the ecological environment [4, 5].

### 2.2. Environmental hazards of electrolytic manganese slag

As a typical solid waste product of the electrolytic manganese industry, the composite pollution caused by the open-air stockpiling of electrolytic manganese slag has become a major contributor to regional environmental risks. Electrolytic manganese slag is rich in heavy metals such as Mn, Cr, Zn, Cu, and Pb. Under the combined effects of sunlight and rainfall, geochemical processes such as oxidation-reduction and dissolution-migration occur, leading to the multi-media diffusion of pollutants. A study by LI et al. on electrolytic manganese slag landfills indicated that the leaching concentrations of Mn, Co, As, and Cu exceeded the Class III limits of the Groundwater Quality Standards by 17.3-fold, 6.8-fold, 4.2-fold, and 3.1-fold, respectively; the study revealed that Mn exhibits extremely high pollution potential[6]. Leaching kinetics experiments in the study by WANG et al. further revealed that the leaching rates of $Mn^{2+}$ and $NH_3$-N were both higher than 65 % within a pH range of 2 – 7, indicating high mobility; among these, the volatilization flux of $NH_3$-N could reach 4.7 mg/($m^2$·h), resulting in ammonia concentrations in the surrounding atmosphere that were 12 – 18 times higher than background levels [7]. Notably, XU's research indicates that the production of 1 t of electrolytic manganese is accompanied by the generation of 7 – 10 t of leachate containing high concentrations of soluble salts. Through leaching, this causes the electrical conductivity of the surrounding soil to exceed 4000 μS/cm, triggering ionic toxicity in plant root systems [8].

Recent ecotoxicological studies indicate that Mn accumulation in earthworms in soils of electrolytic manganese slag-contaminated areas can reach 35 times that of the control group, with significantly inhibited antioxidant enzyme activity, while Cr content in surrounding rice grains reaches 1.87 mg/kg, exceeding food safety standards by 2.3 times [9]. Microbial community analysis revealed that the relative abundance of the Actinobacteria phylum in soils surrounding electrolytic manganese slag storage sites decreased by 62 %, and the expression levels of functional genes in nitrogen-fixing bacteria (such as Bradyrhizobium) dropped to 8 % of those in uncontaminated areas, indicating that combined heavy metal and salinity stress has significantly disrupted the material cycling functions of the soil microecosystem [10]. Together, this multidimensional evidence reveals the cascading destructive effects of electrolytic manganese slag pollution on the "soil-plant-microorganism" system, highlighting the urgency of environmental remediation.

## 3. TECHNOLOGIES FOR THE SAFE DISPOSAL OF ELECTROLYTIC MANGANESE SLAG

Currently, the primary harmless pretreatment technologies used in the electrolytic manganese industry include washing, high-temperature solidification, and leaching [3, 11]. These processes not only ensure harmless disposal but also enable the recovery of resources such as manganese, sulfur, and ammonia from manganese slag for reuse in manganese production [12, 13].

### 3.1. Water-based cleaning technology

Wash treatment is the simplest process for the harmless disposal of manganese slag. It removes most of the soluble salts. This pre-treatment technique involves using clean water to leach out the residual leachate (primarily consisting of $MnSO_4$ and $(NH_4)_2SO_4$) from the manganese slag, which is then reacted with CaO. During the washing process, $Mn^{2+}$ is converted into $Mn(OH)_2$ precipitate, and $NH_4^+$ is converted into $NH_3$, thereby achieving the separation of manganese and ammonia. The chemical reactions during the washing process are as follows:

$$CaO+MnSO_4+H_2O=CaSO_4\downarrow+Mn(OH)_2\downarrow; \quad (1)$$

$$CaO+(NH_4)_2SO_4=CaSO_4\downarrow+2NH_3\uparrow+H_2O. \quad (2)$$

After the reaction, the precipitate – primarily composed of $CaSO_4$ and $Mn(OH)_2$ – is filtered out. $H_2SO_4$ is then used to dissolve the $Mn(OH)_2$ into $MnSO_4$, followed by filtration to separate Mn and Ca. The reaction equation is:

$$Mn(OH)_2+H_2SO_4=MnSO_4+2H_2O. \quad (3)$$

The final solid product consists primarily of $CaSO_4$, which can be utilized as gypsum or calcined to decompose and produce CaO. The reaction equation is:

$$2CaSO_4=2CaO+2SO_2+O_2. \quad (4)$$

The produced CaO can be further utilized in the manganese recovery processes of the first two steps. The $SO_2$ in the flue gas, after purification, conversion, and absorption, forms $H_2SO_4$, which can also be reused in the manganese recovery processes of the first two steps. The water-washed manganese slag is solidified using CaO, converting residual $Mn^{2+}$ and other compounds into forms that are difficult to leach or migrate, thereby immobilizing them within the slag and achieving harmless treatment.

Zheng et al. used pure water to extract soluble manganese from manganese slag and verified through leaching kinetics modeling that, under optimal leaching conditions (solid-to-liquid ratio of 1:4, temperature of 24 °C, and stirring rate of 300 r/min), the extraction rate of soluble manganese reached 83.35 % [14]. Chen et al. investigated the effect of the number of water wash cycles on the removal efficiency of soluble manganese from manganese slag. With a single water wash, the removal rates of soluble manganese and ammonia nitrogen reached 72.35 % and 78.64 %, respectively. As the number of washes increased, the manganese and ammonia nitrogen concentrations in the wash liquid gradually decreased. After four washes, the mass concentration of ammonia nitrogen in the wash liquid was 10.02 mg/L, falling below the national standard requirement of 15 mg/L; However, after 10 washes, the mass concentration of soluble manganese in the wash solution remained above 20 mg/L, indicating that a small amount of soluble salts remained in the manganese slag after washing. This fails to meet relevant standard requirements and poses environmental risks [15]. Water washing enables removal rates of over 90 % for both $MnSO_4$ and $(NH_4)_2SO_4$ in the manganese slag. In the treated

manganese slag, the mass fraction of water-soluble salts is <2%, and the pH, manganese, and ammonia nitrogen levels all meet the requirements for Class I general industrial solid waste [16]. Recovered manganese can be processed into high-concentration, high-purity $MnSO_4$ solutions and returned to the original electrolysis system to minimize impacts on its water and salt balances. Recovered ammonia can be converted into $NH_3 \cdot H_2O$ for reuse in electrolytic manganese production. Additionally, this process enables the recycling of CaO and $H_2SO_4$, reducing chemical consumption and operating costs while delivering stable results.

## 3.2. Solidification technologies for electrolytic manganese slag

### 3.2.1. High-temperature solidification technology

High-temperature solidification technology involves the conversion of some pollutants in manganese slag into stable phases under calcination conditions, while others decompose and are removed from the slag. During calcination, $MnSO_4$ is converted into stable $MnO_2$ [17], and ammonia nitrogen in the manganese slag is removed as ammonia gas under low-temperature calcination with the addition of CaO; the removal efficiency of ammonia nitrogen can reach 99 % [18]. High-temperature solidification technology can involve either direct high-temperature calcination or calcination with the addition of reducing carbon powder [19]. The chemical equations for the high-temperature solidification reactions are:

$$2(NH_4)_2SO_4=4NH_3\uparrow+2SO_2\uparrow+2H_2O\uparrow+O_2\uparrow; \quad (5)$$

$$4MnSO_4=2Mn_2O_3+4SO_2\uparrow+O_2\uparrow; \quad (6)$$

$$3MnSO_4=Mn_3O_4+3SO_2\uparrow+O_2\uparrow; \quad (7)$$

$$MnSO_4=MnO_2+SO_2\uparrow. \quad (8)$$

The released $NH_3$ can be absorbed by dilute $H_2SO_4$ to regenerate $(NH_4)_2SO_4$ in solution. CaO is then added to form a $CaSO_4$ precipitate, while free ammonia is released and sent to an ammonia absorption tower to produce concentrated $NH_3 \cdot H_2O$. The reaction equations are:

$$2NH_3+H_2SO_4=(NH_4)_2SO_4; \quad (9)$$

$$CaO+(NH_4)_2SO_4=CaSO_4\downarrow+2NH_3\uparrow+H_2O. \quad (10)$$

The released $SO_2$ gas is purified, converted, and absorbed to produce $H_2SO_4$. Flue gas desulfurization is performed using the $H_2O_2$ method to ensure compliant emissions, and the resulting $H_2SO_4$ is returned to the absorption system.

Through high-temperature sintering or melting, manganese and other heavy metals in the manganese slag can be completely immobilized within a dense sintered body or molten glass matrix, thereby achieving the safe disposal of the manganese slag. FU et al. revealed the regulatory mechanisms of calcination temperatures ranging from 200 to 1000 °C on the pozzolanic activity and cementing properties of electrolytic manganese slag. The study indicated that heat treatment above 500 °C can reduce the leaching toxicity of $Mn^{2+}$ and $NH_3$-N by more than 90 % [20]. SHU et al. co-treated electrolytic manganese slag with basic combustion raw materials (BRM), reducing the leaching concentrations of $Mn^{2+}$ and $NH_4^+$-N to 0.1 mg/L and 12.8 mg/L, respectively, through the formation of stable mineral phases such as $(Mn, Ca)Si_2O_6$. at a cost of only $10.15/t, while simultaneously passivating heavy metals such as Cr, Cd, and Pb [21]. Zhang et al. found that the decomposition of manganese slag during roasting occurs primarily in the high-temperature range; when roasted at 1000 – 1250 °C, electrolytic manganese slag exhibits significant desulfurization, with $SO_3$ content decreasing from 29.30 % to 7.11 % [22]. Li et al. further proposed a synergistic activation strategy combining mechanical grinding and high-temperature calcination to induce Si–O bond cleavage via $Na_2CO_3$. When the mass ratio of $Na_2CO_3$ to $SiO_2$ was 1:0.5, at a calcination temperature of 900 °C and a duration of 120 min, the effective silicon content in the electrolytic manganese slag increased from 0.19 % to 12.59 %. Leaching test results showed that the $Mn^{2+}$ leaching concentration was below 0.5 mg/L, opening up a new avenue for the preparation of silicon-based materials [23].

After calcination using high-temperature solidification technology, the total content of water-soluble salts in the manganese slag is < 2 %, and the concentrations of manganese and ammonia nitrogen both meet the requirements for Class I general industrial solid waste. Sulfur and ammonia resources in the calcined manganese slag can be fully recovered, and the high-temperature calcined manganese slag exhibits good reactivity, making it suitable for the production of high-value-added building materials or silicon-based materials. High-temperature solidification deeply stabilizes heavy metals through mineral phase restructuring and removes volatile heavy metals; however, it is accompanied by challenges such as high energy consumption and exhaust gas pollution. Additionally, this technology is significantly affected by the price of $H_2SO_4$, resulting in relatively high costs.

### 3.2.2. Chemical solidification technology

Chemical solidification technology stabilizes and recycles harmful components in electrolytic manganese slag through chemical bonding and mineral phase restructuring. SHI et al. developed a $Na_2SiO_3$-NaOH synergistic solidification system. Under optimal conditions – a stirring rate of 450 r/min, an initial pH of 8, a temperature of 40 °C, and a $Na_2SiO_3$ content of 5 % – $Mn(OH)_2$ colloids and $MnSiO_3$ crystals were formed, and FT-IR characterization confirmed the formation of Si-O-Mn bonds. Under this synergistic treatment, the solidification efficiencies of $Mn^{2+}$ and $NH_4^+$-N reached 99.7 % and 98.2 %, respectively, and the compressive strength of the solidification product reached 25 MPa after a curing period of 28 days [24]. LAN et al. innovatively employed a mechanochemical activation process to treat electrolytic manganese slag; by using mechanical force to break the Si-O-Si bonds in the slag, active $SiO_2$ was released and reacted with CaO to form a C-S-H gel. Under conditions of 1.5 % CaO content and a ball milling speed of 500 r/min, ammonia nitrogen in the manganese slag was recovered in the form of NH3 with a recovery rate > 98 %, while the Mn was solidified as $Mn(OH)_2$. At the same time, the electrolytic manganese slag was processed into non-fired bricks (B-EMR) with a compressive strength of 12 MPa. TCLP (Toxicity

Characteristic Leaching Procedure) toxicity leaching tests showed that the leached $Mn^{2+}$ concentration was below 0.1 mg/L, indicating that the mechanochemical activation process successfully achieved the harmless treatment of electrolytic manganese slag [25].

The addition of magnesium oxide or magnesium salts, phosphates, and calcium ions has an immobilizing effect on manganese, ammonia nitrogen, and sulfate ions in manganese slag. CHEN et al. treated manganese slag with $MgSO_4 \cdot 7H_2O$, $Na_3PO_4 \cdot 12H_2O$, and CaO to treat manganese slag; $Mn^{2+}$ was immobilized as $NH_4MgPO_4 \cdot 6H_2O$, $Mn_5(PO_4)_2(OH)_4$, $Mn_3(PO_4)_2 \cdot 3H_2O$, and $Mn(OH)_2$, with immobilization efficiencies reaching 92.4 % and 99.9 %, respectively [26]. LAN et al. added MgO and $CaHPO_4 \cdot 2H_2O$ to manganese slag, causing $Mn^{2+}$ and $SO_4^{2-}$ to be solidified into magnesium ammonium phosphate and calcium sulfate, respectively. The concentrations of $Mn^{2+}$ and other heavy metal ions in the leachate from the solidified manganese slag were all within the limits specified by the Comprehensive Discharge Standard for Wastewater [27].

Red mud and calcium carbide slag can also react with manganese slag to achieve the solidification/stabilization of manganese and ammonia nitrogen. ZHANG et al. utilized alkaline substances in red mud (RM) to treat ammonia nitrogen and soluble manganese ions in manganese slag; ammonia nitrogen was discharged as ammonia gas, while soluble manganese ions were solidified as $Mn_{3.88}O_7(OH)$ and $KMn_8O_{16}$. Under optimal conditions, the removal rates for ammonia nitrogen and manganese were 85.87 % and 86.63 %, respectively [28]. HE et al. investigated the synergistic solidification treatment of calcium carbide slag and manganese slag, where $Mn^{2+}$ was stabilized as $MnFe_2O_4$, $Mn_2SiO_4$, and $CaMnSi_2O_6$, and ammonia nitrogen was released as $NH_3$. In the treated samples, both $Mn^{2+}$ and leaching concentrations were below the detection limits (0.02 mg/L and 0.10 mg/L) [29]. The above studies effectively immobilized Mn and $NH_3$-N in electrolytic manganese slag through chemical solidification pathways, providing important references for the large-scale harmless treatment of electrolytic manganese slag.

All solidification technologies for electrolytic manganese slag can effectively immobilize ammonia nitrogen and heavy metals in the slag; however, significant differences exist among the various technical routes: high-temperature solidification achieves mineral phase restructuring at temperatures ranging from 500 to 1160 °C, simultaneously and efficiently removing volatile heavy metals; however, the high energy consumption of calcination increases treatment costs and requires supporting exhaust gas purification facilities; Chemical solidification can operate at room temperature with low energy consumption, but it relies on the addition of solidification agents, and raw material costs represent a bottleneck limiting the development of the process.

## 3.3. Leaching technology for electrolytic manganese slag

Given that the wet leaching process is the dominant technological approach in the electrolytic manganese industry, establishing a synergistic recovery system for Mn and $NH_3$-N based on the leaching process offers significant dual environmental and economic benefits: on the one hand, by selectively extracting residual manganese and soluble ammonium salts from electrolytic manganese slag, the toxicity of the slag during leaching can be reduced, effectively mitigating the risk of secondary pollution caused by heavy metal migration and ammonia nitrogen volatilization; on the other hand, the recovered manganese resources and ammonia nitrogen components can be directly fed into the electrolytic cell solution circulation system via short-process reuse technology, thereby achieving a closed-loop supply of production raw materials.

### 3.3.1. Chemical leaching

Chemical leaching technology, which selectively leaches valuable components (such as $Mn^{2+}$ and $NH_4^+$) from electrolytic manganese residue (EMR) while simultaneously passivating heavy metal contaminants, has become an effective method for achieving the dual objectives of rendering EMR harmless and recovering its resources.

The low-temperature roasting-water washing process proposed by HE et al., under conditions of 600° C for 60 minutes, achieved a $Mn^{2+}$ leaching rate of 67.12 % through phase transformation, with a $Mn^{2+}$ concentration in the residue below 0.005 g/L, and energy consumption reduced by 55 % compared to high-temperature processes [30]. WEN et al. optimized sulfuric acid leaching conditions using response surface methodology, achieving a $Mn^{2+}$ leaching rate of 99.12 % under conditions of 5.4 mol/L $H_2SO_4$ concentration, a solid-to-liquid ratio of 1:4.8, and a temperature of 80 °C; the leaching process conformed to the Avrami kinetic model. The reaction activation energy was 19.8 kJ/mol, indicating an interfacial chemical reaction control mechanism; however, the chemical leaching process suffers from issues such as high acid consumption and high costs associated with maintaining high temperatures, which limit its economic viability for large-scale application [31]. The $H_2C_2O_4/H_2O_2$ system developed by SUN et al. forms $[Mn(C_2O_4)_3]^{3-}$ complexes through chelation, achieving 93.26 % $Mn^{2+}$ and 92.13 % $NH_4^+$ leaching rates at 25 °C and a 4.16 % $H_2C_2O_4$ concentration; however, organic acid costs account for 65 % of the total cost [32]. The NTA complexation leaching process developed by ZHOU et al. achieved 97.06 % $Mn^{2+}$ recovery within 20 minutes under conditions of 0.015 mol/L NTA concentration and a solid-to-liquid ratio of 1:4; XRD and FT-IR characterization confirmed the formation of a stable mononuclear pentacyclic complex [33]. LI et al. employed a two-stage countercurrent leaching method to extract $Mn^{2+}$, $Mg^{2+}$, and $NH_4^+$ from electrolytic manganese slag. Using α-H-2-EHA (α-hydroxy-2-ethylhexyl phosphinic acid) as the extractant, they enriched $Mn^{2+}$ through two-stage countercurrent extraction and recovered $Mg^{2+}$ and $NH_4^+$ via coprecipitation [34]. The two-stage PbS-$H_2SO_4$-$NH_4Ac$ system designed by RAO et al. achieved selective recovery of Mn and Pb with recovery rates of 98 % and 95 %, respectively, and the leaching agent could be recycled more than five times [35].

Chemical leaching primarily utilizes acidic solutions to selectively leach certain components from manganese slag, yielding good results for manganese recovery. However, the

process requires complex preliminary steps such as grinding, drying, leaching, and filter pressing. It involves high water consumption, relatively high costs, and the potential for secondary pollution, posing significant challenges to its industrial implementation.

### 3.3.2. Bioleaching

Due to its environmental friendliness, low energy consumption, and ability to recover multiple components simultaneously, the microbial leaching method has become a hot topic in research on the green treatment of electrolytic manganese residue (EMR). The metabolic characteristics of different microbial strains offer differentiated solutions for metal recovery and the detoxification of solid waste.

Lan et al. researched the microbial leaching of manganese slag. The results indicated that both non-reducing acids and reducing acids produced by microbial metabolism simultaneously promote the leaching of manganese from the slag, enabling efficient manganese leaching [36]. Lv et al. utilized silicate-activating bacteria to immobilize heavy metals while activating silica; following bioleaching, manganese, cobalt, and nickel formed metal-silicate complexes with silicates, thereby reducing the risk of heavy metal ion leaching [37]. Acidithiobacillus thiooxidans strain Y1, screened by Lan et al., achieved Mn leaching rates of 85 %–98 % under conditions of an 8-day reaction time, a solid-to-liquid ratio of 1:2.5, and the use of waste molasses as a substitute for traditional carbon sources. By adjusting the pH to 8.5–9.0, $(NH_4)_2Mn(SO_4)_2{\cdot}6H_2O$, $(NH_4)_2Mg(SO_4)_2{\cdot}6H_2O$, and $(NH_4)Fe(SO_4)_2{\cdot}6H_2O$ precipitated from the leachate. Microscopic characterization revealed that Thiobacillus Y1 disrupted the surface of electrolytic manganese slag, effectively enhancing leaching efficiency [38]. Lv et al. targeted the silicate components in electrolytic manganese slag, utilizing extracellular polysaccharides secreted by Bacillus mucilaginosus and silicase to dissociate the mineral structure, finding that the silicon leaching efficiency of layered silicates, such as sericite, was significantly higher than that of framework structures. Leaching activity was negatively correlated with the stability of the mineral's Si–O bonds, and the released soluble silicon could be processed into silicon fertilizer to achieve agricultural value-added benefits [39]. Zhao et al. used a Penicillium oxalicum mutant strain Z6-5-1 obtained through directed evolution to increase oxalic acid production to 28.7 g/L. By leveraging a triple mechanism involving $H_2C_2O_4$-$Mn^{2+}$ complexation, acid dissolution, and biological reduction, they achieved a $Mn^{2+}$ leaching rate of 93.3 % within 7 days, while the Fe leaching rate remained < 15 % [40].

Although current biological recovery technologies are simple to operate and have low process costs, they suffer from drawbacks such as long recovery cycles, low efficiency, and complex post-treatment processes, which limit their development for industrial-scale recovery and utilization. The future development of biological methods will depend on the selection and cultivation of bacteria capable of efficiently extracting and recovering manganese and ammonia nitrogen, and greater attention must also be paid to the subsequent treatment and disposal of these bacteria.

### 3.3.3. Electric field-enhanced leaching

The electric field-enhanced leaching technology, driven by the synergistic effects of electromigration, electrodialysis, and electrochemical redox reactions, significantly improves the leaching efficiency and selectivity of valuable metals in electrolytic manganese residue (EMR).

The electric field–$H_2SO_4/H_2O_2$ synergistic system developed by TIAN et al. generates OH radicals at the anode, which promote the dissolution of $MnO_2$ and increase the $Mn^{2+}$ migration rate to $3.2 \times 10^{-5}$ $cm^2/(V{\cdot}s)$. Ultimately, the leaching rates of $Mn^{2+}$ and $NH_4^+$ reached 88.07 % and 91.50 %, respectively. High-purity $MnCO_3$ was recovered via a combined carbonation-phosphate precipitation process, with a manganese recovery rate of 94.2 % [41]. The $Na_2SO_3$-electric field coupled leaching process developed by ZHAO et al. utilized active hydrogen atoms (H*) at the cathode to reduce the reduction potential of $MnO_2$ from 1.23 V to 0.95 V, while simultaneously reducing the reaction activation energy by 31.8 % through chemical reduction with $Na_2SO_3$. Under conditions of 333 K and an electric field strength of 60 $mA/cm^2$, a $Mn^{2+}$ leaching rate of 96.63 % was achieved, and 99 % of $Fe^{3+}$ was retained using electrodialysis membranes to ensure the purity of the leachate. However, this process resulted in a 25 % increase in operating costs due to the continuous addition of $Na_2SO_3$ [42]. Shu et al. further expanded the application scope of electric field technology by inducing the coprecipitation of $Fe^{3+}$ and $Ca^{2+}$ using a 15 V/cm electric field, simultaneously removing $Mn^{2+}$, $NH_4^+$-N, $F^-$, and $PO_4^{3-}$ from electrolytic manganese slag–phosphogypsum leachate, with removal rates of 99.81 %, 58.37 %, 99.90 %, and 99.86 %, respectively. The core mechanisms involved colloidal $Fe(OH)_3$ adsorption at the anode, $NO_3^-$ reduction and denitrification at the cathode, and in situ hydroxyapatite formation for phosphorus removal [43]. LIU et al. employed solar electrokinetic remediation technology to treat manganese slag; under the influence of an electric field, manganese and ammonia nitrogen migrated from the anode chamber to the cathode chamber, and the concentrations of manganese and ammonia nitrogen in the anode chamber continuously decreased, thereby reducing the leaching toxicity of the manganese slag [44].

Studies have shown that electric field enhancement technology can overcome the kinetic limitations of traditional leaching processes through the activation of interfacial reactions, regulation of redox potentials, and synergistic multiphase migration; however, further optimization of chemical consumption and control of residue toxicity is required to improve engineering economics.

## 4. RESEARCH ON COMPREHENSIVE RESOURCE UTILIZATION

The safe disposal of manganese slag can only mitigate its harmful effects; to fully resolve the environmental issues caused by manganese slag, it is necessary to fully utilize it to reduce the proportion of slag ultimately sent to landfills. Currently, the primary methods for the comprehensive utilization of manganese slag include its use as construction

materials, agricultural fertilizers, the recovery of valuable elements, and the production of high-value-added products.

## 4.1. Building materials

Electrolytic manganese slag contains useful components such as $SiO_2$, CaO, $Al_2O_3$, anhydrous calcium sulfate, and dihydrate gypsum, making it a suitable raw material for construction materials such as cement, concrete, bricks, and road base materials [2].

### 4.1.1. Cement production

The main component of manganese slag is gypsum ($CaSO_4 \cdot 2H_2O$), which is an important raw material for cement production. Some theoretical research has been conducted on the use of manganese slag for cement production [45, 46]. Manganese slag contains a significant amount of gypsum, which can be used to activate blast furnace slag for the production of cementitious materials. The resulting cement encapsulates the manganese in the slag, thereby reducing manganese leaching during the utilization process [47, 48]. Bai Min et al. used lime and ball-milled electrolytic manganese slag to prepare eco-friendly cementitious materials. The results showed that when the cement-to-sand ratio was 1:2 and the electrolytic manganese slag content was 70 %, the mechanical properties of various cement mortars reached their optimal levels [49]. Huang Xianjie et al. used a two-step aqueous solution polymerization method to prepare composite cement by combining sodium polyacrylate with electrolytic manganese slag. The test results showed that when the sodium polyacrylate content was 40 %, the ultimate compressive strength of the composite cement was 2.78 MPa [50]. Since electrolytic manganese slag contains a large amount of sulfate ions, incorporating it reduces the stability and durability of ordinary cement. Furthermore, the use of manganese slag to produce ordinary cement requires prior desulfurization and deammonization treatment of the slag; however, this significantly increases production costs, and if desulfurization is ineffective, the resulting ordinary cement exhibits poor stability. Therefore, electrolytic manganese slag is not suitable for large-scale use in the production of ordinary cement. However, elements such as aluminum, silicon, calcium, and iron in the slag are beneficial for the production of sulfoaluminate special cements. Currently, there is a significant body of research on the use of electrolytic manganese slag as an additive in the production of special cements. Zhao Shizhen et al. used electrolytic manganese slag and magnesium slag as additives to produce sulfoaluminate cement. When the addition ratio of both electrolytic manganese slag and magnesium slag was 21 %, under sintering conditions of 1260 °C for 30 minutes, the resulting early-strength, rapid-hardening sulfoaluminate cement exhibited a flexural strength of 5.1 MPa and a compressive strength of 31.2 MPa at 28 days [51].

### 4.1.2. Concrete aggregates

Manganese desulfurization slag produced by high-temperature calcination exhibits weak pozzolanic properties and can be used as an aggregate in concrete production in place of natural crushed stone. Studies have shown that concrete prepared using electrolytic manganese slag modified with quicklime and calcined at 450 °C produces more CSH gel and aluminocalcite (Aft), resulting in significantly improved mechanical properties [1]. Tang et al. prepared a cementitious material rich in aluminate crystals under optimal mixing conditions (60 % manganese slag, 36 % blast furnace slag, and 4 % alkaline activator) and found that the compressive strengths at 3, 7, and 28 days were 34.43, 41.3, and 50.8 MPa, respectively, with a manganese slag utilization rate of 60 % [52]. Chen et al. used quicklime as a modifier to systematically study the influence of different electrolytic manganese slag dosages and calcination temperatures on the mechanical properties of the prepared concrete. The results indicate that concrete prepared from electrolytic manganese slag modified with quicklime and calcined at 450 °C produced more C-S-H gel and aluminocalcite (AFt), effectively improving the mechanical properties of the concrete [53].

### 4.1.3. Unfired bricks

The rapid development of the construction industry has led to a high demand for building bricks, and unfired bricks, as a low-energy, environmentally friendly product, are being actively promoted. Electrolytic manganese slag contains large amounts of quartz, gypsum, and other components suitable for the production of non-fired bricks; therefore, using it to produce non-fired bricks is an ideal channel for the resource utilization of electrolytic manganese slag. Bai Min et al. used manganese slag, cement, recycled brick aggregate, and river sand as raw materials to produce non-fired bricks through mixing, pressing, and curing, and investigated the effect of manganese slag content on the performance of the non-fired bricks. The results indicate that when the manganese slag content does not exceed 10 %, the produced non-fired bricks meet the MU20 requirement (average compressive strength > 20 MPa) after 28 days of natural curing; when the manganese slag content does not exceed 15 %, non-fired bricks with compressive strength meeting the MU15 requirement (average compressive strength ≥ 15 MPa) can be produced [54]. The addition of an appropriate amount of manganese slag promotes the formation of a significant amount of the alunite phase in the unfired bricks, which is beneficial for strength development. WANG et al. used a mixture of manganese slag, blast furnace slag, and gravel to produce non-sintered permeable bricks; after 28 days of curing, the specimens achieved a splitting tensile strength of 3.53 MPa and a permeability of $3.2 \times 10^{-2}$ cm/s, with performance exceeding the requirements of the national standard [55]. Using manganese slag as a raw material for brick production not only consumes large quantities of manganese slag but also reduces production costs, thereby balancing environmental and economic benefits. Since manganese slag contains a large amount of $(NH_4)_2SO_4$, unprocessed manganese slag used to produce unfired bricks may cause salt leaching during use, resulting in efflorescence (also known as alkali efflorescence). Salt has a corrosive effect on the bricks, causing them to powderize and thereby reducing their strength. Since the direct addition of untreated manganese slag can adversely affect the brick-making reaction process and product quality, it must undergo deammonification treatment before use [56].

#### 4.1.4. Subgrade materials

In the field of subgrade materials, manganese slag also shows potential as a blended material. A series of studies has found that manganese slag can be effectively used as a subgrade material after being solidified (common solidifiers include quicklime and cement) or stabilized. Relevant experimental studies indicate that when used as road fill material, solidified/stabilized manganese slag should be blended with sandy soil (at a mass fraction of 30 % or higher). When the mass fraction of manganese slag in cement concrete is less than 15 %, the mechanical and durability properties of the resulting subgrade material meet the requirements for use in road pavement cement concrete.

In analyzing key construction technologies for manganese slag roadbeds, Yin Xinsheng found that when CaO is selected as the solidifier and the CaO content is controlled at 10 %, the ammonia nitrogen concentration in the manganese slag can be kept within the range specified by standards. When the leaching of ammonia nitrogen after solidification meets the standard requirements, the environmental impact of $Mn^{2+}$ concentration is negligible; however, moisture content is a critical influencing factor in this process. The ammonia nitrogen concentration first decreases and then increases with rising moisture content, and the optimal moisture content for manganese slag leaching is 25 % [57]. Bai Yuejiao et al. used electrolytic manganese slag, red mud, and fly ash to jointly produce eco-friendly permeable concrete pavement bricks. The results showed that pavement bricks produced with a 6 % manganese slag admixture had a dense structure, with a splitting tensile strength of 4.09 MPa and a linear failure load of 415.70 N/mm [58]. Tan Bo et al. used steel slag, red mud, and electrolytic manganese slag in combination to prepare subgrade materials. When the mass ratio of steel slag, red mud, and electrolytic manganese slag was 3:1:2, and 4 % cement was added, the resulting pavement material achieved an unconfined compressive strength of 5.48 MPa after 7 days, meeting the compressive strength requirements for subbases under extremely heavy traffic on Class I highways and expressways [59]. Zhang Hailin mixed manganese slag with quicklime and cement, respectively, and employed construction techniques involving filling, compaction, and sealing with manganese slag. The resulting subgrade material exhibited high bearing capacity and met relevant standards [60]. Xu Ming et al. used cement, lime, and fly ash as solidifying agents to solidify manganese slag; the solidified manganese slag, when used as subgrade material for soft soil, demonstrated excellent subgrade performance [61].

### 4.2. Fertilizer production

Electrolytic manganese slag contains manganese, ammonia nitrogen, potassium, and other elements and organic matter essential for crop growth, making it suitable for fertilizer production and offering broad application prospects. Xu Fang et al. applied manganese slag directly to soil as a manganese-containing fertilizer to study its effects on wheat growth. The results showed that the addition of manganese slag significantly promoted wheat growth, with the number of grains per spike and the 100-grain weight increasing by 17.8 % – 25.8 % and 8.74 % – 13.40 %, respectively [62]. Ren Xuehong used high-temperature calcination and microwave digestion to activate the silica in manganese slag, thereby preparing a silicon-manganese compound fertilizer. The results showed that after calcination at 400 °C, the mass fraction of available silicon in the manganese slag reached 6.94 %; after microwave digestion, the mass fraction of available silicon reached 8.08 %, while the mass fraction of water-soluble manganese reached 1.51 % and that of citrate-soluble manganese reached 5.01 %. The activated electrolytic manganese slag can serve as a silicon-manganese fertilizer, providing plants with essential growth elements [63]. Lan Jiaquan et al. utilized manganese slag to prepare compound fertilizers for field application. The results indicated that compound fertilizers prepared from manganese slag significantly promoted the growth and yield of rice, wheat, and rapeseed. Furthermore, the agricultural byproducts were rich in selenium, yielding favorable ecological, social, and economic benefits [64]. The application of appropriate amounts of manganese fertilizer can effectively improve soil fertility, making it a soil fertilizer resource with development potential. However, the long period required for manganese fertilizers to take effect hinders their widespread adoption in agricultural practice [65]. Furthermore, electrolytic manganese slag contains heavy metals such as Cu, Pb, Cd, and Cr, which can easily cause secondary soil contamination, thereby exacerbating the accumulation of harmful substances in the environment. This may lead to the long-term retention and migration of these heavy metals in the soil, potentially causing adverse effects on soil ecosystems and vegetation growth. Research on manganese fertilizers can enhance efficacy, improve performance, and remove harmful elements through the formulation of compound fertilizers, thereby increasing the potential for the effective resource utilization of electrolytic manganese slag.

### 4.3. Recycling of valuable elements

Due to limitations in the electrolytic manganese production process, the resulting electrolytic manganese slag still contains small amounts of manganese, silicon, ammonia nitrogen, sulfates, and other components. This slag has resource recovery value and can be used as a raw material in certain industries. Xie Xuezhen et al. treated electrolytic manganese slag using manganese dioxide as an oxidizing agent and sulfuric acid as a leaching agent. The process involved sequential steps of leaching, iron removal, and extraction to remove impurities. Finally, manganese was recovered from the organic phase via sulfuric acid back-extraction, and the resulting manganese sulfate was concentrated and crystallized to produce high-purity manganese sulfate. The results showed that the total manganese recovery rate could reach 82.6 %, and the prepared high-purity manganese sulfate achieved a purity of 99.78 %. The ammonia-nitrogen wastewater generated after manganese recovery could be further processed to produce ammonia-nitrogen by-products [66]. Yang Xiaohong et al. leached electrolytic manganese slag using hydrochloric acid as the leaching agent. Under conditions of a solid-to-liquid ratio of 1:6, a hydrochloric acid concentration of 2 mol/L, a reaction time of 60 min, and a reaction temperature of

100 °C, the leaching rates of manganese, iron, calcium, aluminum, and $NH_4^+$-N were 95.89 %, 94.69 %, 63.38 %, 2.21 %, and 96.34 %, respectively; after adjusting the pH of the leachate, it can be directly used as fertilizer [67]. Du Bing et al. recovered manganese by adding carbon dioxide and ammonia water to the filtrate of electrolytic manganese slag. The results showed that under certain conditions, the recovery rate of soluble manganese could exceed 75 %, with 27 mg of manganese carbonate recovered from 1 kg of electrolytic manganese slag [68]. HUANG et al. recovered manganese from manganese slag and prepared $MgMn_2O_4$; the magnesium-ion battery cathode material prepared using $MgMn_2O_4$ as a raw material exhibited a high initial reversible capacity [69]. Li Sisi et al. treated electrolytic manganese slag with quicklime; 100 g of quicklime was required per 1 kg of electrolytic manganese slag, with a reaction time of 2 hours. The ammonia precipitation rate in the electrolytic manganese slag reached over 91 %, and the released ammonia gas could be recovered after absorption [70]. LIU et al. used manganese slag leachate to prepare magnesium ammonium phosphate products. When the molar ratio of N, P, and Mg was 1:1.6:1.6, and the pH was 8.0, magnesium ammonium phosphate products with high yield and good purity were obtained [71].

## 4.4. Production of high-value-added products

Current research on high-value-added applications of electrolytic manganese slag has primarily focused on ceramic materials, microcrystalline glass, and adsorbent materials; the materials produced exhibit excellent properties and hold promising prospects for practical applications.

### 4.4.1. Ceramic materials

Since electrolytic manganese slag contains elements similar to those found in kaolin, such as aluminum, silicon, iron, calcium, and magnesium, it can partially replace kaolin in the preparation of ceramic materials. Zhan et al. used electrolytic manganese slag, incinerator fly ash, washed fly ash, and coal fly ash as raw materials to sinter and produce ceramic aggregates. When the mass fractions of these materials were 34.5 %, 20.7 %, 20.7 %, and 24.1 %, respectively, and the mixture was sintered at 1160°C for 12 minutes, 800-grade lightweight ceramic aggregates were successfully produced [72]. Wu et al. used electrolytic manganese slag as the raw material and prepared porous ceramics via the pore-forming method by adding carbon powder, dolomite, and kaolin. The resulting ceramic material had an apparent porosity of 69.70 % and a compressive strength of 6.97 MPa, demonstrating broad application prospects [73]. Liang et al. used electrolytic manganese slag as the primary raw material and added municipal sludge, graphite tailings, and bentonite to fire lightweight porous ceramic aggregates. Under firing conditions of 1130 °C for 15 minutes, they obtained aggregates with a bulk density of 651 kg/m³, an apparent density of 1406 kg/m³, and a cylinder compression strength of 3.78 MPa, meeting national standard requirements [74]. Ke et al. developed sintered ceramic aggregates containing 50 % electrolytic manganese slag. Samples fired at 1050 °C exhibited a compressive strength of 25.03 MPa and a $Mn^{2+}$ leaching concentration of 2.26 mg/L, attributed to a dual stabilization mechanism involving the formation of the $Fe_2MnO_4$ phase and liquid-phase encapsulation [75]. Zhan et al. prepared lightweight ceramic aggregates by co-sintering electrolytic manganese slag with municipal fly ash and coal fly ash. They found that at 1160 °C, Cu, Zn, and Cr were stabilized through solid solution with calcareous minerals; the leaching rates of residual heavy metals met relevant standards; and the escape rates of volatile elements such as Pb and Cd via chlorides exceeded 80 % [76].

### 4.4.2. Microcrystalline glass

Microcrystalline glass is a material in which microcrystalline and glass phases are uniformly distributed. It possesses excellent properties such as low density, impermeability to water and air, high softening temperature, good chemical stability, outstanding thermal stability, high mechanical strength, and high hardness. The main components of manganese slag – $SiO_2$, $Al_2O_3$, CaO, and MgO – are similar to those of raw materials used in glass production; therefore, the use of manganese slag to produce microcrystalline glass has become a viable method for resource recovery. Wang et al. used molten electrolytic manganese slag and ferrochrome slag as raw materials to produce microcrystalline glass with excellent hardness, compressive strength, and acid and alkali resistance. Leaching toxicity tests showed that the leached concentrations of Cr, Pb, and Zn were all below the detection limit, while the leached mass concentration of Mn was only 0.978 mg/L [77]. Qian et al. used electrolytic manganese slag as a raw material and employed a heat treatment process to prepare microcrystalline glass. The specific process is as follows: First, pure electrolytic manganese slag was placed in a crucible and heated at 1350 °C for 1 hour; the molten sample was then rapidly quenched in water to obtain a base glass meeting structural requirements; the base glass was crushed and ground into a 150 μm powder, mixed with an aqueous solution containing 10 % PVA at a mass ratio of 2 %, and pressed into a cake under 30 MPa pressure; finally, after heat treatment, microcrystalline glass with a grain size of 0.5 μm was prepared [78]. Liu et al. prepared microcrystalline glass from manganese slag using both the melting and sintering methods. Experimental results showed that when the heat treatment temperature was 950 °C, the manganese slag utilization rates for the melting and sintering methods reached 95 % and 100 %, respectively [79]. The large consumption of manganese slag in the production of microcrystalline glass effectively addresses the problem of massive stockpiles of electrolytic manganese slag and helps broaden the avenues for resource utilization of manganese slag.

### 4.4.3. Zeolite adsorbent materials

Molecular sieves are a class of crystalline aluminosilicate materials with a regular pore structure. Due to their excellent adsorption, ion exchange, and catalytic properties, they are widely used in the petrochemical and environmental protection industries. Electrolytic manganese slag is rich in aluminum and silicon and can serve as a raw material for synthesizing zeolite molecular sieves. Active sites such as Si–O–Al in manganese slag

confer adsorption properties; however, untreated manganese slag exhibits poor adsorption performance due to limitations in particle size and pore size. Through physical or chemical modification, the specific surface area of manganese slag increases, exposing more adsorption sites and thereby enhancing its adsorption performance.

Zeng et al. removed iron impurities from electrolytic manganese slag through acid leaching, then mixed the purified slag with sodium carbonate and subjected it to high-temperature activation at 750 °C. The activated manganese slag was added to a 2 mol/L sodium hydroxide solution and mixed with $Na_2SiO_3 \cdot 9H_2O$ (ANA-S) and $NaAlO_2$ (ANA-A), respectively, to synthesize electrolytic manganese slag-based ANA-S and ANA-A zeolites via an 8-hour hydrothermal reaction. Measurements showed that the saturation adsorption capacities of these two zeolites were 185.19 mg/g and 161.29 mg/g, respectively, with $Pb^{2+}$ removal rates of 95.47 % and 93.69 % for an initial concentration of 100 mg/L [80]. Sun Yan et al. used modified electrolytic manganese slag to prepare an adsorbent for trivalent arsenic ions, with the modified material exhibiting an adsorption capacity of up to 19.98 mg/g for arsenic ions. Under simulated wastewater conditions with an arsenic ion concentration of 50 mg/L, the arsenic content in the treated wastewater was reduced to 0.042 mg/L, meeting the national Class II surface water environmental standard [81]. Ma Mengyu et al. prepared a composite adsorbent using electrolytic manganese slag and calcite, achieving a maximum adsorption capacity of 435.69 mg/g for cadmium ions and a removal rate of 99.2 % [82]. Ma Shicheng et al. prepared manganese slag-red mud composite adsorbents and iron hydroxide adsorbents by extracting effective manganese and iron components from electrolytic manganese slag. The experimental results showed that the adsorption capacity of the iron-based adsorbent for copper ions increased from 0 to 12.801 mg/g, while the adsorption capacity of the manganese slag-red mud adsorbent for copper ions increased from 4.70 mg/g to 62.55 mg/g [83]. Ma et al. employed a one-step method to prepare polyacrylic acid-polyacrylamide hydrogel adsorbents from electrolytic manganese slag. The results indicated that the hydrogel adsorbent exhibited high selective adsorption capacities for lead, cadmium, and copper ions, with adsorption capacities of 153.85, 113.63, and 54.35 mg/g, respectively [84]. Lan et al. modified electrolytic manganese slag with sodium hydroxide and prepared a novel adsorbent using methods such as ultrasonic etching and microwave-assisted processing to remove tetravalent arsenic ions from wastewater. The experimental results showed that the maximum adsorption capacity of the novel adsorbent for arsenic ions was 23.96 mg/g, indicating that electrolytic manganese slag-based adsorbents have practical value in the field of arsenic removal [85]. Li et al. modified manganese slag using ethylenediaminetetraacetic acid (EDTA). The modified manganese slag exhibited a maximum adsorption capacity of 133.46 mg/g for sodium diethyldithiocarbamate in mineral processing wastewater, outperforming many other adsorbents, with the adsorption sites of transition metals (Mn, Fe) playing a primary role in the removal of sodium diethyldithiocarbamate [86]. Huang et al. used manganese slag treated with KOH and ultrasonic etching as an adsorbent to remove $Cu^{2+}$, and the treated wastewater fully met discharge standards [87].

Electrolytic manganese slag can serve as an ideal raw material for adsorbing various heavy metals and dyes and holds potential for the production of high-value-added products. However, the adsorption capacity of electrolytic manganese slag-based materials currently needs improvement; modification, compositing, and various pretreatment methods are required to remove impurities from the slag and enhance its structural properties. Overall, the use of electrolytic manganese slag as a wastewater treatment material is currently an effective method of resource recovery, broadening the scope of applications for high-value-added products derived from electrolytic manganese slag.

## 5. CONCLUSIONS

Electrolytic manganese slag, a major industrial solid waste generated during the production of electrolytic manganese, is stored in massive quantities and contains characteristic pollutants such as $Mn^{2+}$, $NH_4^+$-N, and $SO_4^{2-}$, posing a serious threat to the ecological environment. Safe disposal and resource recovery are the fundamental solutions to these environmental issues.

Currently, harmless disposal technologies primarily include water washing, high-temperature solidification, and chemical solidification. While these methods effectively reduce the leaching toxicity of manganese slag, they generally suffer from high energy consumption, high costs, or the need for large amounts of chemical additives. Resource recovery pathways encompass multiple directions, including construction materials (cement, concrete, unburned bricks, roadbed materials), agricultural fertilizers, recovery of valuable elements, and the production of high-value-added products (ceramics, microcrystalline glass, adsorbents). Although significant progress has been made in research, several common challenges remain: First, many utilization pathways require extensive pretreatment of manganese slag, increasing process complexity and costs; second, the performance stability, long-term environmental safety, and market acceptance of certain products remain to be verified; third, there is a lack of cost-effective, large-scale application technologies, and the overall utilization rate remains low.

Future research should focus on the following areas:

1. Developing new integrated technologies for synergistic harmless treatment and resource recovery that are low-energy, low-cost, and highly efficient;
2. Deepening fundamental research on the speciation of pollutants in manganese slag, their migration and transformation patterns, and stabilization mechanisms to provide theoretical support for precise regulation;
3. Expanding high-value-added utilization pathways, particularly the development of functional materials for strategic emerging industries such as new energy and environmental protection;
4. Strengthening life-cycle assessments and economic analyses to facilitate the transition of technologies from the laboratory to engineering and industrialization, ultimately achieving the large-scale consumption and green recycling of electrolytic manganese slag.

*Acknowledgments*

The work was supported by the Hubei Science and Technology Development Special Project (Project number: 42000025205T00000018901).

**REFERENCES**

1. **Haoyu, G., Zhibin, Z., Tao, Y., Yang, L., Guifang, W.** Research Status and Application Trends of Electrolytic Manganese Residue Resource Utilization *Modern Mining* 40 (4) 2024: pp. 220 – 225. https://doi.org/10.3969/j.issn.1674-6082.2024.04.052
2. **Jiale, L., Tingyong, W., Pingchao, K., Yipeng, Z., Lingling, X.** Research Progress on Harmless and Resource Treatment Technology of Electrolytic Manganese Residue *Inorganic Chemicals Industry* 3 (2) 2025: pp. 1 – 12. https://doi.org/10.19964/j.issn.1006-4990.2025-0126
3. **Lihong, M., Yifeng, P.** Research on Resource Treatment Technology of Electrolytic Manganese Residue *Shandong Chemical Industry* 52 (17) 2023: pp. 252 – 255. https://doi.org/10.19319/j.cnki.issn.1008-021x.2023.17.057
4. **Sen, H., Bingping, Y., Zhongqiu, L., Liqi, C.** Study on Physicochemical Properties of Electrolytic Manganese Residue *Technology & Development of Chemical Industry* 51 (11) 2022: pp. 41 – 46. https://doi.org/10.3969/j.issn.1671-9905.2022.11.009
5. **Hong, G., Lili, H., Bo Y, Bangbang M, Minjie Y, Yuting L**. Analysis of Electrolytic Manganese Slag Characteristics and Study of Influencing Factors in Southwest China *Journal of Safety and Environment* 24 (1) 2024: pp. 280 – 289. https://doi.org/10.13637/j.issn.1009-6094.2022.2046
6. **Li, C., Zhong, H., Wang, S., Xue, J.** Leaching Behavior and Risk Assessment of Heavy Metals in a Landfill of Electrolytic Manganese Residue in Western Hunan, China *Human and Ecological Risk Assessment: An International Journal* 20 (5) 2014: pp. 1249 – 1263. https://doi.org/10.1080/10807039.2013.849482
7. **Wang, D., Wang, Q., Xue, J.** Reuse of Hazardous Electrolytic Manganese Residue: Detailed Leaching Characterization and Novel Application as a Cementitious Material *Resources, Conservation and Recycling* 154 2020: pp. 104645. https://doi.org/10.1016/j.resconrec.2019.104645
8. **Xu, F., Jiang, L., Dan, Z., Gao, X., Duan, N., Han, G., Zhu, H.** Water Balance Analysis and Wastewater Recycling Investigation in Electrolytic Manganese Industry of China-a Case Study *Hydrometallurgy* 149 2014: pp. 12 – 22. https://doi.org/10.1016/j.hydromet.2014.05.002
9. **Fu, Y., Qiao, H., Feng, Q., Chen, K., Li, Y., Xue, C., Zhang, Y.** Review of New Methods for Resource Utilisation of Electrolytic Manganese Residue and its Application in Building Materials *Construction and Building Materials* 401 2023: pp. 132901. https://doi.org/10.1016/j.conbuildmat.2023.132901
10. **He, S., Jiang, D., Hong, M., Liu, Z.** Hazard-Free Treatment and Resource Utilisation of Electrolytic Manganese Residue: A Review *Journal of Cleaner Production* 306 2021: pp. 127224. https://doi.org/10.1016/j.jclepro.2021.127224
11. **Jinrong, X.** A Research Progress on Harmless Treatment Technology and Resource Utilization of Electrolytic Manganese Residue *China Manganese Industry* 38 (6) 2020: pp. 1 – 6. https://doi.org/10.14101/j.cnki.issn.1002-4336.2020.06.002
12. **Yi-ming, L., Si-lu, D., Wan-ping, X.** An Engineering Case of the Harmless Treatment and Resource Reuse for Electrolytic Manganese Residue *Nonferrous Metallurgical Equipment* 34 (5) 2020: pp. 1 – 3. https://doi.org/10.19611/j.cnki.cn11-2919/tg.2020.05.001
13. **Linling, J., Chao, Y., Zhiwei, D., Faming, C., Yong, Y., Hanke, W., Liming, Q.** A Study on Recycle and Utilization Technology of $CO_2$ and its Application in Electrolytic Manganese Industry *China Manganese Industry* 40 (3) 2022: pp. 48 – 53. https://doi.org/10.14101/j.cnki.issn.1002-4336.2022.03.008
14. **Zheng, F., Zhu, H., Luo, T., Wang, H., Hou, H.** Pure Water Leaching Soluble Manganese from Electrolytic Manganese Residue: Leaching Kinetics Model Analysis and Characterization *Journal of Environmental Chemical Engineering* 8 (4) 2020: pp. 103916. https://doi.org/10.1016/j.jece.2020.103916
15. **Hufei, C., Xiaozhi, C., Mao, Z., Bo, Y., Kai, K., Yongjun, M.** An Experimental Study on Water Washing and Solidification of Electrolytic Manganese Slag *China Manganese Industry* 41 (6) 2023: pp. 1 – 4. https://doi.org/10.14101/j.cnki.issn.1002-4336.2023.06.001
16. **Zhipeng, K., Ye, L., Bo, Y., Minjie, Y., Bangbang, M., Yuting, L.** Treatment of Electrolytic Manganese Slag by Water Washing Combined Curing Method *Chinese Journal of Environmental Engineering* 17 (1) 2023: pp. 235 – 241. https://doi.org/10.12030/j.cjee.202209069
17. **Duan, N., Cui, K., Zhu, C., Jin, S.** Study on Phase Evolution and Promoting the Pozzolanic Activity of Electrolytic Manganese Residue During Calcination *Environmental Research* 227 2023: pp. 115774. https://doi.org/10.1016/j.envres.2023.115774
18. **Huang, L., Li, X., Li, Q., Wang, Q., Zhao, F., Liu, W.** Ammonia Removal and Simultaneous Immobilization of Manganese and Magnesium From Electrolytic Manganese Residue by a Low-Temperature Cao Roasting Process *Environmental Science and Pollution Research* 31 (7) 2024: pp. 11321 – 11333.

https://doi.org/10.1007/s11356-024-31895-0

19. **Chao, Z., Shuai, W., Hong, Z., Lin, Q.** Review on Decontamination and Resource Utilization of Electrolytic Manganese Residue Technology *Conservation and Utilization of Mineral Resources* 39 (3) 2019: pp. 111 – 118. https://doi.org/10.13779/j.cnki.issn1001-0076.2019.03.018
20. **Fu, Y., Qiao, H., Feng, Q., Chen, K., Li, Y., Jis, Z.** Self-Stabilisation of High-Temperature Calcined Electrolytic Manganese Residue in Mortar *Construction and Building Materials* 386 2023: pp. 131460. https://doi.org/10.1016/j.conbuildmat.2023.131460
21. **Shu, J., Li, B., Chen, M., Sun, D., Wei, L., Wang, Y., Wang, J.** An Innovative Method for Manganese ($Mn^{2+}$) and Ammonia Nitrogen ($Nh_4^+$-N) Stabilization/Solidification in Electrolytic Manganese Residue by Basic Burning Raw Material *Chemosphere* 253 2020: pp. 126896. https://doi.org/10.1016/j.chemosphere.2020.126896
22. **Hai-yan, Z., Fei-bao, Y.** The Resource Utilization of High Temperature Calcined Electrolytic Manganese Slag *Energy Conservation & Environmental Protection* 9 2021: pp. 77 – 78. https://doi.org/10.3969/j.issn.1009-539X.2021.09.026
23. **Li, J., Du, D., Peng, Q., Wu, C., Lv, K., Ye, H., Chen, S., Zhan, W.** Activation of Silicon in the Electrolytic Manganese Residue by Mechanical Grinding-Roasting *Journal of Cleaner Production* 192 2018: pp. 347 – 353. https://doi.org/10.1016/j.jclepro.2018.04.184
24. **Shi, Y., Long, G., Wang, F., Xie, Y., Bai, M.** Innovative Co-Treatment Technology for Effective Disposal of Electrolytic Manganese Residue *Environmental Pollution* 335 2023: pp. 122234. https://doi.org/10.1016/j.envpol.2023.122234
25. **Lan, J., Zhang, S., Mei, T., Dong, Y., Hou, H.** Mechanochemical Modification of Electrolytic Manganese Residue: Ammonium Nitrogen Recycling, Heavy Metal Solidification, and Baking-Free Brick Preparation *Journal of Cleaner Production* 329 2021: pp. 129727. https://doi.org/10.1016/j.jclepro.2021.129727
26. **Chen, H., Long, Q., Zhang, Y., Qin, L.** Simultaneous Immobilization of $Nh_4$+ and $Mn^{2+}$ from Electrolytic Manganese Residue Using Phosphate and Magnesium Sources *RSC Advances* 9 (8) 2019: pp. 4583 – 4590. https://doi.org/10.1039/C8RA09615E
27. **Lan, J., Sun, Y., Tian, H., Zhan, W., Du, Y., Ye, H., Du, D., Zhang, T.C., Hou, H.** Electrolytic Manganese Residue-Based Cement for Manganese Ore Pit Backfilling: Performance and Mechanism *Journal of Hazardous Materials* 411 2021: pp. 124941. https://doi.org/10.1016/j.jhazmat.2020.124941
28. **Zhang, J., Li, R., Zhang, Y., He, W., Yang, J., Wang, Y.** Study on Mutual Harmless Treatment of Electrolytic Manganese Residue and Red Mud *Environmental Science and Pollution Research* 30 (21) 2023: pp. 59660 – 59675. https://doi.org/10.1007/s11356-023-26752-5
29. **He, D., Shu, J., Zeng, X., Wei, Y., Chen, M., Tan, D., Liang, Q.** Synergistic Solidification/Stabilization of Electrolytic Manganese Residue and Carbide Slag *Science of The Total Environment* 810 2022: pp. 152175. https://doi.org/10.1016/j.scitotenv.2021.152175
30. **He, S., Wilson, B.P., Lundström, M., Liu, Z.** Hazard-Free Treatment of Electrolytic Manganese Residue and Recovery of Manganese Using Low Temperature Roasting-Water Washing Process *Journal of Hazardous Materials* 402 2021: pp. 123561. https://doi.org/10.1016/j.jhazmat.2020.123561
31. **Wen, Q., Liu, B., Zhang, J., Shen, H., Lu, X., Wang, S., Zhang, S.** Efficient Leaching of Manganese From Electrolytic Manganese Residue and Recovery of the Leaching Solution: Reuse and Purification *Separation and Purification Technology* 332 2024: pp. 125648. https://doi.org/10.1016/j.seppur.2023.125648
32. **Sun, C., Zhang, Y., Yang, Y., Shang, Q., Liu, Y., Chen, Q.** Research on Leaching Behavior of Manganese and Ammonia Nitrogen in Electrolytic Manganese Residue Under Oxalic Acid/Hydrogen Peroxide System *Journal of Water Process Engineering* 63 2024: pp. 105405. https://doi.org/10.1016/j.jwpe.2024.105405
33. **Zhou, Y., Wu, S., Liu, R., Liu, Z., Tao, C.** Efficient Recovery of Manganese and Ammonia Nitrogen from Filter-Pressing Electrolytic Manganese Residue by Organic Complexation *Journal of Water Process Engineering* 45 2022: pp. 102532. https://doi.org/10.1016/j.jwpe.2021.102532
34. **Li, X., Li, X., Yang, J., Cao, Z., Li, C., Xue, J., Ma, X., Wang, S.** Highly Efficient $Mn^{2+}$, $Mg^{2+}$, and $Nh_4^+$ Recovery From Electrolytic Manganese Residue Via Leaching, Solvent Extraction, Coprecipitation, and Atmospheric Oxidation *Journal of Hazardous Materials* 472 2024: pp. 134430. https://doi.org/10.1016/j.jhazmat.2024.134430
35. **Rao, S., Sun, J., Wang, D., Liu, Z., Zhu, W., Cao, H., Duan, L.** Selective Recovery of Manganese and Lead from Electrolytic Manganese Residues in a Sulfuric Acid Solution with Galena as the Reductant *Separation and Purification Technology* 308 2023: pp. 122937. https://doi.org/10.1016/j.seppur.2022.122937
36. **Lan, J., Sun, Y., Chen, X., Zhan, W., Du, Y., Zhang, T.C., Ye, H., Du, D., Hou, H.** Bio-Leaching of Manganese From Electrolytic Manganese Slag by Microbacterium Trichothecenolyticum Y1: Mechanism and Characteristics of Microbial Metabolites *Bioresource Technology* 319 2021: pp. 124056. https://doi.org/10.1016/j.biortech.2020.124056
37. **Lv, Y., Li, J., Ye, H., Du, D., Li, .J, Sun, P., Ma, M., Wen, J.** Bioleaching Behaviors of Silicon and Metals in Electrolytic Manganese Residue Using Silicate

Bacteria *Journal of Cleaner Production* 228 2019: pp. 901 – 909. https://doi.org/10.1016/j.jclepro.2019.04.289

38. **Lan, J., Sun, Y., Guo, L., Li, Z., Du, D., Zhang, T.C.** A Novel Method to Recover Ammonia, Manganese and Sulfate from Electrolytic Manganese Residues by Bio-Leaching *Journal of Cleaner Production* 223 2019: pp. 499 – 507. https://doi.org/10.1016/j.jclepro.2019.03.098
39. **Lv, Y., Li, J., Ye, H., Du, D., Sun, P., Ma, M., Zhang, T.C.** Bioleaching of Silicon in Electrolytic Manganese Residue (Emr) by Paenibacillus Mucilaginosus: Impact of Silicate Mineral Structures *Chemosphere* 256 2020: pp. 127043. https://doi.org/10.1016/j.chemosphere.2020.127043
40. **Zhao, S., Zheng, B., Wang, Y., He, F., Wang, L., Lin, X., Luo, X., Feng, J.** Environmentally-Friendly Biorecovery of Manganese from Electrolytic Manganese Residue Using a Novel Penicillium Oxalicum Strain Z6-5-1: Kinetics and Mechanism *Journal of Hazardous Materials* 446 2023: pp. 130662. https://doi.org/10.1016/j.jhazmat.2022.130662
41. **Tian, Y., Shu, J., Chen, M., Wang, J., Wang, Y., Luo, Z., Wang, R., Yang, F., Xiu, F., Sun, Z.** Manganese and Ammonia Nitrogen Recovery from Electrolytic Manganese Residue by Electric Field Enhanced Leaching *Journal of Cleaner Production* 236 2019: pp. 117708. https://doi.org/10.1016/j.jclepro.2019.117708
42. **Zhao, Z., Wang, R., Shu, J., Chen, M., Xu, Z., Xue, T., Zeng, X., He, D., Tan, D., Deng, Z.** Enhanced Manganese Leaching from Electrolytic Manganese Residue by Electrochemical Process and $Na_2so_3$ *Minerals Engineering* 189 2022: pp. 107862. https://doi.org/10.1016/j.mineng.2022.107862
43. **Shu, J., Zhao, J., Wei, X., Chen, M., Li, B., Gao, Y., Yang, Y., Deng, Z.** Synergistic Harmless Treatment of Phosphogypsum Leachate Wastewater with Iron-Rich Electrolytic Manganese Residue and Electric Field *Minerals Engineering* 204 2023: pp. 108399. https://doi.org/10.1016/j.mineng.2023.108399
44. **Liu, R., Wang, H., Liu, Z., Tao, C.** Electrokinetic Remediation with Solar Powered for Electrolytic Manganese Residue and Researching on Migration of Ammonia Nitrogen and Manganese *Journal of Water Process Engineering* 38 2020: pp. 101655. https://doi.org/10.1016/j.jwpe.2020.101655
45. **Wang, F, Long, G., Bai, M., Wang, J., Shi, Y., Zhou, X., Zhou, J.L.** A New Perspective on Belite-Ye'elimite-Ferrite Cement Manufactured from Electrolytic Manganese Residue: Production, Properties, and Environmental Analysis *Cement and Concrete Research* 163 2023: pp. 107019. https://doi.org/10.1016/j.cemconres.2022.107019
46. **Zhao, S.Z., Han, F.L., Liu, G.Q., Li, M.H., Chen, Y.J.** Preparation and Mechanical Performance of Sulpoaluminate Cement by Using Industrial Solid Wastes *Key Engineering Materials* 726 2017: pp. 510 – 514. https://doi.org/10.4028/www.scientific.net/KEM.726.510
47. **Shujun, C., Zongshuo, T., Xuebao, S.** Study on Application of Manganese Slag as Cement Mixture *China Building Materials Science & Technology* 28 (4) 2019: pp. 48 – 49.
48. **Yonggang, Z., Xun, W., Yida, H.** The Cement Process Helps the Recycling of Manganese Slag *China Cement* 7 2022: pp. 72 – 74. https://doi.org/10.3969/j.issn.1671-8321.2022.07.016
49. **Min, B., Guangcheng, L.** Preparation of Ecological Cement-Based Materials with Low Strength by Mixing Large Amount of Electrolytic Manganese Residue *New Building Materials* 50 (6) 2023: pp. 55 – 60. https://doi.org/10.3969/j.issn.1001-702X.2023.06.012
50. **Xianjie, H., Yue, W., Jue, Z., Daikuan, H., Yang, C., Dabin, Z.** Research on Anti-Seepage Performance of Polyacrylate Composite Electrolytic Manganese Slag Cementitious Materials *Metal Mine* 1 2023: pp. 283 – 288. https://doi.org/10.19614/j.cnki.jsks.202301035
51. **Shizhen, Z., Fenglan, H., Yaguang, W.** Preperation of Composite Slag Sulphoaluminate Cement Clinker From Electrolytic Manganese-Magnesium *Bulletin of the Chinese Ceramic Society* 36 (5) 2017: pp. 1766 – 1772. https://doi.org/10.16552/j.cnki.issn1001-1625.2017.05.053
52. **Tang, L., He, Z., Chen, K., Wang, X., Xiao, Y., Yu, Z., Xiao, H.** Study of Microscopic Properties and Heavy Metal Solidification Mechanism of Electrolytic Manganese Residue-Based Cementitious Materials *Environmental Science and Pollution Research* 30 (48) 2023: pp. 105056 – 105071. https://doi.org/10.1007/s11356-023-29772-3
53. **Aoao, C., Qin, Z., Xianhai, L.** Influence of Quicklime/Calcined Modified Electrolytic Manganese Slag on the Performance of Cement Concrete *Conservation and Utilization of Mineral Resources* 43 (1) 2023: pp. 155 – 161. https://doi.org/10.13779/j.cnki.issn1001-0076.2023.07.003
54. **Min, B., Guangcheng, L., Youjun, X., Fan, W., Yingying, S., Tianyang, Z.** Properties and Application of Non-Fired Bricks Prepared from Manganese Slag and Recycled Brick Aggregates *Bulletin of the Chinese Ceramic Society* 41 (10) 2022: pp. 3533 – 3541. https://doi.org/10.16552/j.cnki.issn1001-1625.20220726.003
55. **Wang, Y., Gao, S., Liu, X., Tang, B., Mukiza, E., Zhang, N.** Preparation of Non-Sintered Permeable Bricks Using Electrolytic Manganese Residue: Environmental and $Nh_3$-N Recovery Benefits *Journal of Hazardous Materials* 378 2019: pp. 120768. https://doi.org/10.1016/j.jhazmat.2019.120768

56. **Xiaoyu, Y., Jiawei, W., Haifeng, W., Pingyuan, Z.** Study on Water Absorption and Saturation Coefficient of Sintered Brick with Electrolytic Manganese Slag *Multipurpose Utilization of Mineral Resources* 6 2022: pp. 89 – 93. https://doi.org/10.3969/j.issn.1000-6532.2022.06.016
57. **Xinsheng, Y.** Analysis on Key Technology of Manganese Slag Subgrade Construction in Road Engineering *Transpoworld* 28 2022: pp. 64 – 66. https://10.3969/j.issn.1006-8872(s).2022.10.021
58. **Yuejiao, B., Ye, L., Bangbang, M., Bo, Y., Yuting, L.** Mechanical Properties and Leaching Toxicity of Electrolytic Manganese Residue-Red Mud-Coal Fly Ash Paving Bricks *Research of Environmental Sciences* 37 (2) 2024: pp. 388 – 396. https://doi.org/10.13198/j.issn.1001-6929.2023.11.03
59. **Bo, T., Qi, L., Ping, C.** Study on Preparation and Properties of Subgrade Water Stabilized Materials with Steel Slag,Red Mud and Electrolytic Manganese Slag *Journal of Wuhan University of Technology* 43 (8) 2021: pp. 51 – 56. https://doi.org/10.3963/j.issn.1671-4431.2021.08.008
60. **Hailin, Z.** An Exploration of Application of Electrolytic Metal Manganese Residue Inecological Friendly Highway Roadbed Construction *China Manganese Industry* 42 (1) 2024: pp. 107 – 110. https://doi.org/10.14101/j.cnki.issn.1002-4336.2024.01.019
61. **Ming, X., Zhihong, W., Sihai, W., Lingdong, M., Luheng, G.** A Research on Application of Stabilized Electrolytic Manganese Slag in Soft Soil Roadbed Filling *China Manganese Industry* 42 (2) 2024: pp. 84 – 88. https://doi.org/10.14101/j.cnki.issn.1002-4336.2024.02.016
62. **Fang, X., Xingmin, W., Jinlian, X., Dejian, D., Lin, C.** Nutrition Effect of Mn in Manganese Tailings on Wheat Growth *Guizhou Agricultural Sciences* 38 (8) 2010: pp. 56 – 58. https://doi.org/10.3969/j.issn.1001-3601.2010.08.020
63. **Xuehong, R.** A Study of Preparation of Manganese Fertilizer from Emm Slag *China Manganese Industry* 35 (3) 2017: pp. 145 – 147. https://doi.org/10.14101/j.cnki.issn.1002-4336.2017.03.041
64. **Jiaquan, L., Huaian, W.** Waste Dregs of Emm for Usage of Crops *China Manganese Industry* 4 2006: pp. 23 – 25. https://doi.org/10.3969/j.issn.1002-4336.2006.04.006
65. **Qiuhong, M.** Study on the Status and Treatment Countermeasures of Manganese Industrial Pollution:an Example from Guizhou Province *China Manganese Industry* 41 (5) 2023: pp. 1 – 6. https://doi.org/10.14101/j.cnki.issn.1002-4336.2023.05.001
66. **Xue-zhen, X., You-ming, Y., Yuan-hua, W., Jun, Z.** Study on Preparation of High-Purity Manganese Sulfate From Electrolytic Manganese Slag *Nonferrous Metals (Extractive Metallurgy)* 9 2021: pp. 84 – 89. https://doi.org/10.3969/j.issn.1007-7545.2021.09.014
67. **Xiao-hong, Y., Xin, X., Xi-shi, X.** Study on Acid Leaching Experimental Conditions of Electrolytic Manganese Residue *Bulletin of the Chinese Ceramic Society* 37 (7) 2018: pp. 2326 – 2330. https://doi.org/10.16552/j.cnki.issn1001-1625.2018.07.044
68. **Du, B., Zhou, C., Ming, Z., Xiaocheng, P., Junli, M., Qianqian, P.** Recovery of Soluble Manganese from Electrolytic Manganese Residue *Environmental Protection of Chemical Industry* 30 (6) 2010: pp. 526 – 529. https://doi.org/10.3969/j.issn.1006-1878.2010.06.016
69. **Huang, L., Li, X., Hu, J., Deng, Q., Yang, C., Liu, W., Zhao, F., Jiang, H.** Recovery of Manganese as Spinel $MgMn_2O_4$ Cathode Material from Electrolytic Manganese Residue by $Na_2Co_3$ Hydrothermal-Roasting Process *Separation and Purification Technology* 336 2024: pp. 126248. https://doi.org/10.1016/j.seppur.2023.126248
70. **Sisi, L., Chaoxia, Y., Yang, L., Qinli, D.** Recycling of Ammonia from Electrolytic Manganese Residue *Journal of Jishou University (Natural Sciences Edition)* 37 (4) 2016: pp. 57 – 60. https://doi.org/10.3969/j.cnki.jdxb.2016.04.012
71. **Liu, X., Ren, Y., Zhang, Z., Liu, X., Wang, Y.** Harmless Treatment of Electrolytic Manganese Residue: Ammonia Nitrogen Recovery, Preparation of Struvite and Nonsintered Bricks *Chemical Engineering Journal* 455 2023: pp. 140739. https://doi.org/10.1016/j.cej.2022.140739
72. **Zhan, X., Wang, L.A., Wang, L., Gong, J., Wang, X., Song, X., Xu, T.** Co-Sintering Mswi Fly Ash with Electrolytic Manganese Residue and Coal Fly Ash for Lightweight Ceramisite *Chemosphere* 263 2021: pp. 127914. https://doi.org/10.1016/j.chemosphere.2020.127914
73. **Wu, F.F, Li, X.P., Zhong, H., Wang, S.** Utilization of Electrolytic Manganese Residues in Production of Porous Ceramics *International Journal of Applied Ceramic Technology* 13 (3) 2016: pp. 511 – 521. https://doi.org/10.1111/ijac.12502
74. **Qingyang, L., Fei, X., Xuquan, H., Xiaorong, Z., Haojie, W., Zilong, H., Jun, W.** Study on Mechanism of Preparation of Porous Ceramsite and Fixation of Heavy Metal Manganese from Electrolytic Manganese Slag and Multi-Source Solid Waste *Inorganic Chemicals Industry* 57 (8) 2025: pp. 102 – 109. https://doi.org/10.19964/j.issn.1006-4990.2024-0491
75. **Ke, X., Chen, X., Wang, T., Wang, D., Ma, S., Li, J., Bao, S., Jing, Z.** Immobilization Mechanism of $Mn^{2+}$ in Electrolytic Manganese Residue Using Sintered Ceramsites Prepared by Alkali-Mechanical-Roasting Method *Journal of Environmental Chemical Engineering* 12 (2) 2024: pp. 112419. https://doi.org/10.1016/j.jece.2024.112419
76. **Zhan, X., Wang, Y., Wang, L.A., Li, C., Xu, X., Deng, R.** Migration, Solidification/Stabilization Mechanism of Heavy Metal in Lightweight Ceramisite

From Co-Sintering Fly Ash and Electrolytic Manganese Residue *Process Safety and Environmental Protection* 173 2023: pp. 485 – 494. https://doi.org/10.1016/j.psep.2023.03.047

77. **Wang, J., Han, F., Yang, B., Liu, T.** One-Step Preparation of Glass-Ceramics From a Ferrochrome Slag and an Electrolytic Manganese Slag *Advanced Engineering Materials* 25 (8) 2023: pp. 2201529. https://doi.org/10.1002/adem.202201529
78. **Qian, J., Hou, P., Wang, Z., Qu, Y.** Crystallization Characteristic of Glass-Ceramic Made from Electrolytic Manganese Residue *Journal of Wuhan University of Technology-Mater. Sci. Ed.* 27 (1) 2012: pp. 45 – 49. https://doi.org/10.1007/s11595-012-0404-8
79. **Yajuan, L., Fenglan, H.** Orthogonal Experimental Study on Preparation of Glass-Ceramics from Electrolytic Manganese Residue *China Ceramics* 56 (1) 2020: pp. 62 – 66. https://doi.org/10.16521/j.cnki.issn.1001-9642.2020.01.011
80. **Yue, Z., Xu-li, L., Yu-chi, C., Sha, W., Min, Z., Hao-bo, H.** Preparation of Analcite Based on Electrolytic Manganese Slag and Study on its $Pb^{2+}$ Adsorption Property *Environmental Engineering* 38 (11) 2020: pp. 175 – 179. https://doi.org/10.13205/j.hjgc.202011029
81. **Yan, S., Jirong, L., Li, G., Peng, S., Hengpeng, Y., Du, D., Wei, Z.** Preparation of as (III) Adsorbent Material by Electrolytic Manganese Slag and its Properties *CIESC Journal* 70 (6) 2019: pp. 2377 – 2385. https://doi.org/10.11949/j.issn.0438-1157.20181536
82. **Mengyu, M., Hua, W., Xiaolong, S., Cheng, J., Weiya, W., Kaifu, T., Jis, L.** Adsorption Behaviors of Cd(II) by Electrolytic Manganese Residues-Calcite Composite Adsorbent *Non-Metallic Mines* 43 (3) 2020: pp. 89 – 92. https://doi.org/10.3969/j.issn.1000-8098.2020.03.025
83. **Shicheng, M., Zaimei, M., Hannian, G., Tengfei, G., Yang, D., Ning, W.** Preparation of Manganese Residue-Bauxite Residue Adsorbent and its Adsorption Capacity on $Cu^{2+}$ *Inorganic Chemicals Industry* 52 (3) 2020: pp. 85 – 89. https://doi.org/10.11962/1006-4990.2019-0228
84. **Ma, M., Ke, X., Wang, T., Li, J., Ye, H.** A Novel Double-Network Hydrogel Made from Electrolytic Manganese Slag and Polyacrylic Acid-Polyacrylamide for Removal of Heavy Metals in Wastewater *Journal of Hazardous Materials* 462 2024: pp. 132722. https://doi.org/10.1016/j.jhazmat.2023.132722
85. **Lan, J., Sun, Y., Guo, L., Du, Y., Du, D., Zhang, T.C., Li, J., Ye, H.** Highly Efficient Removal of as (V) with Modified Electrolytic Manganese Residues (M-Emrs) as a Novel Adsorbent *Journal of Alloys and Compounds* 811 2019: pp. 151973. https://doi.org/10.1016/j.jallcom.2019.151973
86. **Li, M., Hu, L., Zhong, H., He, Z., Sun, W., Xiong, D.** Efficient Removal of Diethyl Dithiocarbamate with Edta Functionalized Electrolytic Manganese Residue and Mechanism Exploration *Journal of Hazardous Materials* 410 2021: pp. 124582. https://doi.org/10.1016/j.jhazmat.2020.124582
87. **Huang, Y., Zhang, Q.** Highly Efficient Removal of Cu(II) with Modified Electrolytic Manganese Residue as a Novel Adsorbent *Arabian Journal for Science and Engineering* 47 (5) 2022: pp. 6577 – 6589. https://doi.org/10.1007/s13369-021-06506-6

© Tan et al. *2027* Open Access This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (http://creativecommons.org/licenses/by/4.0/), which permits unrestricted use, distribution, and reproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made.