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Review

Approaches for electroplating sludge treatment and disposal technology: Reduction, pretreatment and reuse

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ABSTRACT

Electroplating sludge (ES) has become an obstacle to the sustainable development of the electroplating industry. Electroplating sludge has a large storage capacity, with a high concentration of soluble pollutants (heavy metals), which has great potential to harm the local ecosystems and human health. Although much research has been done in this area, there seems to be no mature and stable solution. Therefore, the latest technologies for the reduction, pretreatment and reuse of electroplating sludge are emphatically introduced based on the analysis of the characteristics of electroplating sludge and its impact on the ecological environment. The factors hindering the treatment and disposal of electroplating sludge are pointed out, and reasonable and feasible suggestions to solve this problem are proposed. The solidification and removal mechanism of heavy metals in electroplating sludge is emphatically analyzed. The physicochemical and separation processes of heavy metals, as well as thermal treatment technique are discussed. Finally, it is proposed to establish a database of the physicochemical properties and elemental content of electroplating sludge to achieve its systematic treatment and digestion. We hope that this paper can help solve the problem of electroplating sludge and promote the sustainable development of the electroplating industry.

1. Introduction

Industrial electroplating process and surface treatment produce a large amount of wastewater. By the end of 2021, there were more than 10,000 electroplating plants and more than 5000 electroplating production lines in China, which discharged approximately 400 million tons of wastewater containing heavy metals every year (Qu et al., 2021). The chemical treatment has become the main method for treating electroplating wastewater due to its advantages of low initial cost, mature process, low use conditions, and high degree of electrical control (Quiton et al., 2022). Other methods include ion exchange (Cao et al., 2013), activated carbon method (Gupta et al., 2009; Ramrakhiani et al., 2022; Aliakbari et al., 2017), electrolysis method (Wang et al., 2022a), electrodeionization method (Lu et al., 2015), reverse osmosis method (Un et al., 2017; Sharma et al., 2020a, 2020b; Kong et al., 2020; Reddithota et al., 2007), and biological method (Malaviya and Singh, 2016). It has been reported that the proportion of electroplating wastewater treated by chemical methods in China is approximately 41%, while in Japan, the proportion is as high as 85%. Electroplating wastewater is often treated by chemical neutralization and flocculation sedimentation, resulting in a large amount of electroplating sludge with high water content, easy accumulation, poor stability, easy transfer and other characteristics (Dayananda et al., 2009).

The secondary environmental harm of electroplating sludge is greater than that of electroplating wastewater. Various organic substances are often added in the electroplating process to improve the quality of electroplating products, such as brighteners, levelling agents, surfactants. Most of them are harmful substances, such as sodium allylsulfonate, alkynol, citric acid, malic acid and acetone (Tavares and Franco, 2012). The treatment of wastewater is more difficult and the composition of sludge is more complex because of the addition of these substances (Golder et al., 2009). In the process of treatment, heavy metals in electroplating wastewater are transferred to electroplating sludge, making the sludge contain a large number of heavy metals, such as Cu, Ni, Cr, Zn, Pb and Cd (Datsenko et al., 2021; Dung et al., 2015; Vijay and Sihorwala, 2003). Electroplating sludge is classified as the 17th category of hazardous waste in China's National Catalogue of Hazardous Wastes, and is also recognized as a worldwide hazardous waste (Xia et al., 2020). If they are arbitrarily stacked without proper treatment, the heavy metals will migrate along the path of

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sludge-soil-crop-human body under the action of rainwater leaching, not only polluting the environment, causing serious pollution to groundwater but also directly or indirectly harming human health (Bai et al., 2011; Nair et al., 2008). At present, there is no unified and safe way to thoroughly treat electroplating sludge. Generally, factories dispose of sludge by themselves or by delivering it to qualified companies for landfill disposal or by government departments for unified disposal along with domestic waste. However, Japan, the United States and Western Europe have a high degree of specialization in sludge treatment, and all have special electroplating sludge treatment plants. Generally, separated electroplating sludge with economic value is sent to smelting metal, while mixed electroplating sludge is usually solidified.

Electroplating sludge contains a variety of nonferrous metal components, and its grade is higher than that of metal-rich ores. According to statistics, electroplating enterprises in China produce approximately 10 million tons of electroplating sludge every year (Wang et al., 2022b), the European Union produces approximately 100,000 tons of electroplating sludge every year, and the total amount of electroplating sludge produced in the rest of the world exceeds 1 million tons every year. In the current situation of the large consumption of natural metal resources, the resource utilization of electroplating sludge is not only a fundamental requirement for environmental protection but also an important means of sustainable development and a circular economy. Therefore, it is of great significance to treat electroplating sludge reasonably and cautiously.

At present, many scientific research institutions have done much practical work, gained much practical treatment experience, and have also made good technological progress. However, in general, there is no mature and reliable method to completely solve the problem of electroplating sludge disposal. To maximize the recovery of useful resources and strictly control secondary pollution in the process of processing and utilization is the treatment technology in line with the concept of the circular economy and scientific development. At present, most electroplating sludge is simply stacked or landfilled, causing serious environmental pollution and wasting metal resources. Therefore, research on how to treat electroplating sludge innocuously as a resource has always been a hot spot in related fields.

The reduction of electroplating sludge can be realized from the source. Pretreatment can remove the pollutants in electroplating sludge, and reused through valuable metal recovery and material utilization. At present, the stabilization/solidification and thermochemical method are widely used in the industrial application of electroplating sludge treatment. Among them, cement solidification is the most commonly used solidification technology, with a low treatment cost, but not all valuable resources have been recovered. Moreover, with increasingly strict environmental requirements, the cost of cement solidification will increase dramatically (Silva et al., 2007). The thermochemical method has the advantages of volume reduction, weight reduction and toxicity reduction, but it has high energy consumption and strict equipment requirements. The disposal process of solidification landfilling or stockpiling is simple, but there is a secondary pollution problem caused by the slow release of heavy metals, which wastes valuable metal resources. At present, most studies focus on the recovery of some valuable metals from electroplating sludge, but the process of comprehensive recovery of valuable metals from mixed electroplating sludge by full wet treatment has not been developed (Sun et al., 2021). Electroplating sludge has dual characteristics of pollution and resource, so it is the focus of current research to recycle it to a certain extent on the premise of ensuring that it is harmless (Magalhaes et al., 2004). Electroplating sludge contains a variety of heavy metals and is an excellent raw material for preparing ferrite (Chen et al., 2017), ceramic materials (Wang and Liu, 2018; Tang et al., 2014), adsorbents (Liang et al., 2021), catalysts (Wang et al., 2021a) and electrode materials (Lei et al., 2020).

Although several researchers have been engaged in the study of electroplating sludge treatment, there are still some deficiencies at present. This paper comprehensively summarizes the most advanced technologies and the current research status of the reduction, pretreatment and reuse of electroplating sludge, emphasizes the factors hindering the pollution control and recycling of electroplating sludge, analyses the advantages and limitations of existing electroplating sludge treatment and disposal technologies, and proposes reasonable and feasible suggestions.

2. Physicochemical properties of electroplating sludge

The electroplating process, composition of the electroplating solution, wastewater treatment process and purification objectives will affect the physical and chemical properties of electroplating sludge. The understanding of its chemical and mineral composition is the premise to realize the reasonable treatment and application of electroplating sludge. In general, electroplating sludge has the characteristics of high moisture content, large heavy metal mass fraction, high thermal stability and easy to cause secondary pollution.

2.1. Physical properties

Electroplating sludge is a kind of alkaline substance with a pH between 6.7 and 9.77 (Huang et al., 2022; Peng et al., 2020a). Its volatile component content is approximately 10–20% of dry basis and ash content is more than 76% (Peng et al., 2020b). Generally, electroplating enterprises will carry out plate and frame pressure filtration treatment on the initial sludge generated from wastewater treatment, and the water content of the obtained electroplating sludge is 60%~90%, in the form of block or sludge. Some enterprises will air dry the filtered sludge to reduce the treatment cost, thereby reducing its water content to 30% ~40%, in granular or powder form. The sludge particle size produced by different electroplating types varies greatly, which may be related to the nucleation and growth mode of particles in the process of sludge formation, mostly concentrated in the range of 1–500 μm.

2.2. Chemical properties

The electroplating process mainly includes single metal electroplating, such as copper plating and nickel plating, as well as binary alloy and multielement alloy electroplating, so the types and contents of metal elements in electroplating sludge are different. Its potential value is very high, and it is often used to prepare functional materials. Different functional materials have different requirements for raw materials, so a database of electroplating sludge element information can be established. Establishing a systematic and comprehensive electronic library of chemical properties of electroplating sludge is of utmost importance. In this paper, the types and contents of the main elements in electroplating sludge are collected and listed by consulting relevant documents, as shown in Table 1.

2.3. Mineral composition

The chemical composition and material composition of electroplating sludge are very complex and unevenly distributed. The sludge particles are simply stacked together, belonging to a mixed system with low crystallinity and fine crystal size. It contains a variety of phases such as spinel, gypsum, phosphate, and a large number of amorphous substances. The heavy metals are mostly in the form of hydroxide colloids and lattice substitution. The research shows that the crystallinity of the calcined sludge is still not high. The hydroxide in the calcined electroplating sludge decomposes and reacts with Cu, Ni and other metals to form minerals such as double oxide and spinel. The calcined products also include bauxite, $CaSO_4$ and other components.

Table 1
Common types and components of electroplating sludge.

Electroplating type		wt.%								Processing method	Ref.
		Ca	Cr	Fe	Co	Ni	Cu	Zn	Si		
Separate sludge	Zn	–	2.5	7.1	–	7.0	4.8	22.2	–	Catalytic agent	Chen et al. (2017)
	Ni	0.6	–	3.2	–	91.6	–	–	–	Ni-based composite nanomaterials	Hou et al. (2021)
	Cr	0.79	12.90	9.74	–	–	10.95	–	–	Glass-ceramics	Lin et al. (2021)
	Cr	–	63	12	–	4	3	6	1	Adsorbent	Kabtamu et al. (2020)
	Fe	–	0.06	25.6	5.5	–	–	–	0.9	Nanometer material	Liu et al. (2020)
Mixed sludge	Fe–Cu–Cr	15.09	4.98	20.86	–	3.49	7.62	1.61	0.56	Adsorption material	Peng et al. (2020b)
	Cu–Cr–Ni	12.44	3.91	7.55	–	6.02	5.13	–	3.04	Smelt	Yu et al. (2021a)
	Cu–Ni	10.8	0.4	19	–	9.5	1.70	1.60	–	Denitration catalyst	Zhang et al. (2014)
	Fe– Zn	–	2.93	20.25	–	2.12	–	9.88	–	Pigment	Milanez et al. (2005)
	Fe–Cu	2.24	0.02	20.32	–	0.45	14.50	0.06	–	Ferrite	Chen et al. (2010)
	Cr–Ni	1.09 (CaO)	15.29	0.654 (Fe_2O_3)	–	25.86	2.23	1.581	5.63 (SiO_2)	Pottery and porcelain	Carneiro et al. (2018a)

2.4. Microstructure

The particles of electroplating sludge are irregular and approximately 50 nm in size. These nanoparticles are gathered together without obvious crystal morphology. As seen from the EDS diagram, heavy metals are evenly distributed and doped with each other in the amorphous nanoparticles (Fig. 1).

3. Electroplating sludge reduction

Reduction of electroplating sludge means minimizing volume and quality. At present, the output of electroplating sludge is increasing year by year, the capacity of sludge landfill is in short supply, the cost of landfills disposal is increasing year by year, and the transportation cost of secondary utilization of electroplating sludge is high. Therefore, sludge reduction can reduce the treatment and disposal costs and logistics costs, and can also significantly reduce the energy consumption of smelting rings, which has good economic and environmental benefits. The reduction of electroplating sludge can be started from source reduction and end control.

3.1. Source reduction

The most important thing to reduce electroplating sludge is source reduction and reducing the amount of input and output materials in the electroplating process. Therefore, in the electroplating process, it is necessary to save water, improve the repetition rate of industrial water, and minimize impurities such as Ca and Mg in the water. Improving the electroplating process is the key to sustainable development, including reducing the carry-out liquid to reduce the amount of cleaning water and reducing the concentration of toxic and harmful substances such as heavy metals in the electrolytic bath solution. The decontamination of the workpiece should be strengthened before electroplating to reduce the amounts of pollutants attached to the workpiece. The electroplating operation level and productivity are improved by establishing a triple-objective MIDO model (Liu et al., 2012).

3.2. End control

With the increasingly stringent requirements for the discharge of electroplating pollutants, the concentration of pollution factors in the water discharged up to the standard becomes increasingly lower, and more toxic and harmful substances will enter the sludge. To meet stricter discharge standards, it is necessary to increase the input of wastewater treatment agents, and the output of electroplating sludge is bound to rise. Therefore, to realize the reduction of electroplating sludge, it is also necessary to do a good job in the end control: (1) Classify electroplating wastewater. The finer the classification is, the better the treatment of wastewater and the lower the input of wastewater treatment agents. For example, for Cr-containing wastewater, compared with the traditional process of directly adding $FeSO_4$ and lime, adding appropriate iron filings can greatly reduce the sludge volume and chromium content of sludge, and the treatment effect is better (Luo, 2018). (2) Adopt high-quality wastewater treatment agents to reduce the use of lime. Qualified wastewater is used instead of fresh water to configure agents to reduce fresh water input. (3) Optimize the wastewater treatment

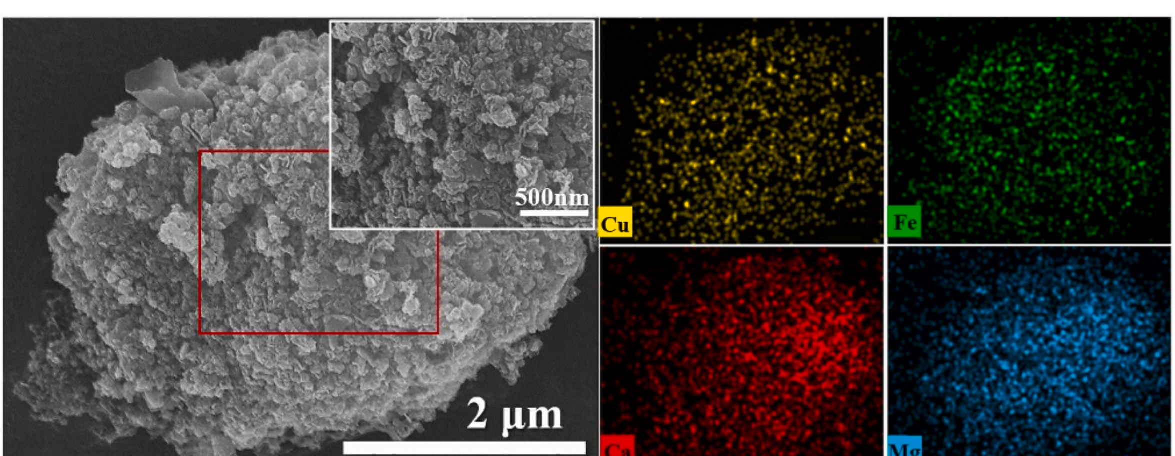

Fig. 1. SEM image of the electroplating sludge and elemental maps from the higher magnification image (Yu et al., 2021b).

process, adopt automatic operation, and improve operation accuracy. (4) Adopt efficient treatment to reduce the water content of sludge.

3.3. Reduce water content

The research shows that the volume and quality of sludge with a water content of 90% is twice that of sludge with a water content of 80%. When the water content continues to drop to 50%, the sludge quality will drop again by 60% (Rao et al., 2019). Therefore, deep dewatering of sludge is particularly important. The practice shows that the water content of sludge cannot be lower than 60% after treatment by traditional thickening and dewatering processes, and the most economical mechanical dewatering sludge water content is approximately 75%. Therefore, many researchers improve its dehydration through pretreatment, such as adding lime, $FeCl_3$ or polymer, heating, freeze−thaw treatment, ultrasound, microwave radiation and oxidation (Tao et al., 2020; Faruqi et al., 2021). After high-pressure filtration, the water content of pretreated electroplating sludge will be reduced to below 55%, its weight and volume will be greatly reduced, and its storage will be safer and more convenient.

Among them, heat treatment is the most mature pretreatment method at present. Heat treatment can remove most of the water and organic matter in the sludge, greatly reduce its mass and volume, and increase the content of heavy metals, which is conducive to subsequent recovery and material utilization. Most importantly, soluble ions can migrate from soluble components to low bioavailability components after heat treatment and transform into stable chemical forms, such as metal oxides in solid residues, significantly reducing their ecotoxicity. When the treatment temperature is higher than 900 °C, most of the low volatile ions, such as Cu^{2+}, Cr^{6+}, Cd^{2+} and Ni^{2+}, can easily be incorporated into the heterogeneous spinel solid solution (Li et al., 2022a). However, the biggest disadvantage of this method is energy consumption. Therefore, it is still necessary to find an energy-saving dehydration process to treat electroplating sludge economically and effectively.

3.4. Limiting factors and future development

Although many methods can reduce electroplating sludge, there are some limitations. For example, due to the complex composition and high moisture content of electroplating sludge, the efficiency and effect of a single method are not good. Reducing the water content of electroplating sludge should be combined with the electroplating operation process. From the practice of electroplating enterprises, the source reduction method has a small investment and good effect, but it has high technical requirements for enterprises. If the technical strength of enterprises is insufficient, it is difficult to implement these measures or the effect after implementation is very small. The end control method has a good effect, but the investment is large, and the operation cost will also increase. At present, the research and development of automatic processes and equipment is relatively small. In practice, to pursue profits and ensure production, electroplating enterprises are not willing to change the production process. Therefore, much remains need to be done.

4. Electroplating sludge pretreatment

After pressure filtration, electroplating sludge still contains high concentrations of heavy metals, which affects its subsequent treatment and disposal. Therefore, the high mobility heavy metals should be removed or stabilized/solidified before the secondary application of electroplating sludge. After pretreatment, electroplating sludge is no longer a “hazardous industrial solid waste” and will not harm the environment, but will be an available resource for industrial production.

4.1. Removal and extraction of heavy metals

The main methods for extracting heavy metals from electroplating sludge include wet treatment, thermochemical method and biological method, as shown in Table 2. Appropriate treatment methods should be flexibly adopted according to the physical and chemical properties of sludge. The wet process is the most mature and commonly used treatment method, including acid leaching and ammonia leaching. Then purification processes such as chemical precipitation (Bian et al., 2021; Swinder and Lejwoda, 2021), solution extraction (Silva et al., 2006), ion exchange (Evaristo et al., 2013), electrowinning (Peng and Tian, 2010; Wu et al., 2021; Wang et al., 2018) and pressurized hydrogen are used for further separation and purification. And ultrasound can enhance the leaching of heavy metals (Zhang et al., 2013). H_2SO_4, which is cheap, volatile and difficult to decompose, and $NH_3 \cdot H_2O$ with moderate alkalinity and recyclability are most commonly used. Xu et al. (2015) used ammonia/ammonium solution as the leaching agent, N902 as the extractant, and sulfuric acid as the stripping agent to determine the optimal process conditions for a total recovery rate of 93.6% and 88.9% for Cu and Ni, respectively. Organic acids are also commonly used to treat electroplating sludge due to their synergistic effects. For example, Cu was extracted from electroplating sludge with a mixed solution of EDTA and citric acid. The recovery rate of copper was 82.21%, and the extraction solution still had the same leaching capacity after three cycles (Deng et al., 2022) (Fig. 2 (a)). Using benzoic acid complexation precipitation to separate Cr and Fe, the separation rate of Fe is 97.38%, and the loss rate of Cr is only 3.59% (Li et al., 2021). The optimal leaching rates of Cr and Cu were 80.02% and 92.89%, respectively, when using a mixture of citric acid and nitric acid to treat electroplating sludge (Chen and Wang, 2012). Nguyen et al. (Manh Khai et al., 2021) used a three-stage treatment process to treat electroplating sludge in polyacrylic acid (PAA) solution, resulting in removal rates of Ni and Cu as high as 99.7% and 99.72%, respectively. Wet leaching can achieve selective leaching of metals. Cr and Fe in electroplating sludge are difficult to separate due to their similar properties. If phosphate is used to selectively separate Cr and Fe, the recovery rate of Cr can be 97.04% under the optimum conditions, while the precipitation rate of Fe is only 14.75% (Yan et al., 2019). Li et al. (2019) reached similar conclusions.

At present, the thermal treatment of electroplating sludge is a process of thermal decomposition, deep oxidation or melting of sludge components. Through thermal treatment, sludge can be reduced, and the existing forms of some elements can be changed for recycling. Among them, the smelting method, as one of the pyrometallurgical methods, uses coal and coke as fuel and reducing substances, with auxiliary materials such as iron ore and limestone, mainly to recover Ni and Cu from electroplating sludge. Yu et al. (2021a) cotreated sludge with copper slag and cathode carbon, and found that the recovery rates of Cr, Ni and Cu can reach 75.56 wt%, 98.41 wt% and 99.25 wt%, respectively, and the leaching toxicity of the slag is small. The treated slag is generally used as raw material for building materials. In the complex multiphase reaction process of heat treatment, various reactions may be intertwined, and various metal oxides generated by decomposition interact, so it is difficult to analyze the reaction rules of single components and products (Fig. 2 (b)). Moreover, after thermal pretreatment, such as chlorination roasting (Liu et al., 2022), sodium roasting (Wang et al., 2022c) and calcium roasting (Huang et al., 2013), the sludge reduction and metal enrichment effect is significant, which is conducive to subsequent wet metal recovery. For example, Huang et al. (2022) found that the recovery rates of Zn, Cu and Cr in electroplating sludge after chlorination treatment reached 99%, 98% and 96%, respectively. After further extraction and purification, the purity of Cr and Zn reached 92% and 99%, respectively. If water leaching occurs after the chlorination phase change, the recovery of Ni and Cu can reach 96.3% and 90.7%, respectively, and water leaching is gentler and more environmentally friendly than acid leaching (Huang et al., 2021a). In addition, in the pretreatment process, by controlling the reaction conditions to change

Table 2
Extraction and purification of heavy metals in electroplating sludge.

Processing method	Principle	Advantages	Disadvantages	Ref.
Thermochemical method	The process of adding reducing substances and slagging agents in the sludge smelting process, and reacting to obtain metal or metal intermediate products under high temperature conditions.	Simple and convenient operation.	High energy consumption, large investment and low metal recovery rate.	Yu et al. (2021a)
Wet process	Under the appropriate leaching environment, valuable metals in ES enter the solution and are initially separated from impurities. Purification of leaching solution to extract metals or prepare related metal products.	Acid leaching: high leaching rate; Ammonia leaching: easy to selectively separate.	Acid leaching: serious equipment corrosion and poor operating environment. Ammonia leaching: high requirements for device sealing, the leaching solution is volatile, and the environmental hazard is great.	Bian et al. (2021)
Chemical precipitation method	The different solubility products of precipitation formed by metal ions under different solution pH, different precipitation dose and other conditions.	Mature technology and widespread use.	Long process flow and large consumption of precipitator, acid and alkali.	Swinder and Lejwoda (2021)
Solution extraction	Transfer the metal ions in the solution to another phase that is basically insoluble with the metal ion solution system, thus realizing the extraction and separation of metals.	Fast reaction speed, strong operation continuity, good separation effect and few impurities.	The organic phase in electroplating sludge affects the extraction phase separation, resulting in emulsification.	Silva et al. (2006)
Ion exchange method	According to the different exchange capacity of the active group of the ion exchange resin to different metal ions in the solution, the resin selectively adsorbs metal ions.	Simple process operation and good metal ion selectivity.	The treatment capacity is small, the speed is slow, and high requirements for stability of solution system.	Evaristo et al. (2013)
Electrowinning method	Under a certain applied voltage, the migration of metal ions in the solution system and the redox reaction process on the electrode surface occur. The target metal continuously deposits at the cathode.	Capable of treating complex leaching solution.	Electrode equipment is easily worn.	Peng and Tian (2010)
Combined pyroroasting-wet process	The ES is pretreated by fire process to remove water, organic matter and some impurities, classify and enrich valuable metals, and then leach valuable metals with appropriate leaching agent.	It can realize the extraction and separation of some metals that are difficult to separate in the wet process, and is suitable for treating sludge with complex components.	Long process flow, high energy consumption and large production investment.	Huang et al. (2021a)
Biological method	Using the biological acid-producing effect of autotrophic thiobacillus acidophilus, the insoluble heavy metals are dissolved from the solid phase into the liquid phase to become soluble metal ions, and then recovered from the leaching solution. The mechanism of action includes the growth, metabolism, adsorption, and transformation of microorganisms.	Good economy, easy control of process flow and friendly environment.	The reaction time is long, the consumption is large, and the microorganism is sensitive to environmental changes. The limits this method: 1) Heavy metals in ES are highly toxic to microorganisms. 2) ES is mainly composed of metal salts or hydroxides, lacking N, P for microbial growth and metabolism. 3) Due to the special physicochemical properties of ES and the harshness of the leaching system, cultivating or domesticating microorganisms with specific leaching functions and strong adaptability is difficult.	Prabhu and Baskar (2015)

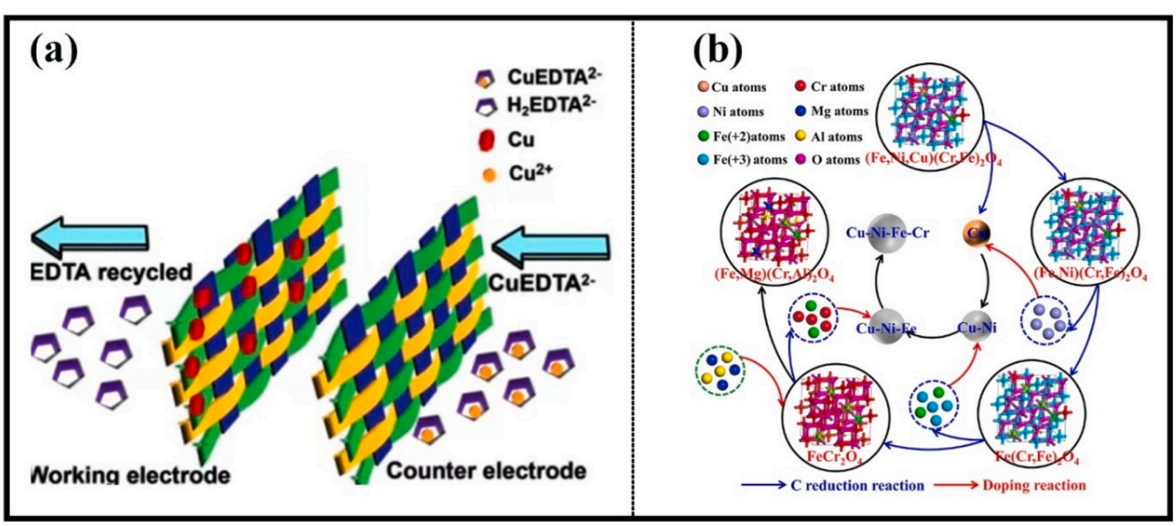

Fig. 2. (a) Leaching electrodeposition mechanism diagram (Deng et al., 2022). (b) Transformation behavior of spinel ((Cu, Fe, Ni)(Fe, Cr)$_2$O$_4$) during vitrification (Yu et al., 2021a).

the occurrence state of the metal, directional conversion of the metal can be achieved, thus achieving selective recovery (Wang et al., 2022d). Zheng et al. (2020) achieved a recovery rate of 99.9% of Cr through crystal modification. Yu et al. (2021b) achieved the selective recovery rate of nearly 97% for Cu in electroplating sludge after chlorination pretreatment, and the purity of the $CuCl_2 \cdot 2H_2O$ product is approximately 95%.

At present, there are few reports on the treatment of electroplating sludge by biological leaching, and the treatment mechanism is quite complex, including the growth, metabolism, adsorption, transformation, and other processes of microorganisms. The research mainly focuses on how to reduce the toxicity of heavy metal ions in sludge to microorganisms and cultivate better strains. At present, Thiobacillus ferrooxidans (Prabhu and Baskar, 2015) and Thiobacillus thiooxidans can effectively leach valuable metals from electroplating sludge, and researchers have also cultivated other strains. For example, salt-tolerant gram-negative bacteria can tolerate high concentrations of Cr^{6+}, and the removal rate of Cr^{6+} can reach 81% (100 mg/L) within 48 h (Kalola and Desai, 2020). The recovery rates of Cr and Ni were 53% and 95.7%, respectively, by Aspergillus niger (Nikfar et al., 2020). Bacillus also has a good absorption effect on Cr^{6+} (Liu et al., 2008). Through the bioleaching of sludge by a medium thermophilic consortium, the leaching rate of various metals (Cu, Ni, Cr, Zn) can reach more than 99% (Zhou et al., 2019), and the residue after leaching can be reused as building materials. Sun et al. (2021) mixed three bacterial strains (Leptospirillum ferriphilum CS13, Acidithiobacillus caldus S2 and Sulfobacillus acidophilus TPY) in equal proportions for biological leaching, and the results showed that the copper leaching efficiency reached 94.3% on the 7th day (21.1% higher than chemical leaching), and the residue can be used in the construction industry. Tian et al. (2022) used response surface methodology to optimize the indirect biological leaching process (mixed strains of sulfur-oxidizing strains, ferrous/sulfur-oxidizing strains and ferrous-oxidizing strains), and obtained maximum leaching rates of Ni, Cu, Zn, and Cr of 100%, 96.5%, 100%, and 76.1%, respectively. They were superior to H_2SO_4 in removing highly toxic Cr (76.1% vs 30.2%). Mixing multiple bacterial strains may be a promising direction, but some researchers believe that microbial mixed leaching has neither resistance nor synergistic effects. Bacteria have a strong selectivity for heavy metals, and the addition of surfactants or humic acids may have a positive effect on the metal leaching rate. Microbial cultivation usually takes a long time (30 days approximately), making it difficult to apply in engineering practice.

Each method has its advantages and disadvantages, which are listed in Table 2. Multiple methods of combined treatment or cascade treatment should be selected based on the characteristics of raw materials and actual conditions to achieve efficient pre-treatment of electroplating sludge.

4.2. Stabilization/solidification of heavy metal ions

Due to the large base of electroplating sludge, various treatment technologies are still immature. At present, electroplating sludge is mainly treated by solidification/stabilization technology (see Table 3). Its basic mechanism is to mix electroplating sludge with a solidification agent, and through enhanced treatment, fix the heavy metal ions in the sludge in the lattice without being leached to prevent heavy metal migration. Curing technology mainly includes lime solidification, cement solidification, thermoplastic solidification, melting solidification, etc. Cement, lime, asphalt and Na_2SiO_3 are common curing agents.

The cement solidification method has been widely used because of its remarkable effect on electroplating sludge treatment, high efficiency, low price, stable technology, mature process and easy availability of solidification materials. The amount of cement should be greater than the amount of sludge to ensure the solidification effect. The long-term stability of heavy metals in cement solidified bodies and the high compatibilization rate of cement solidification have been issues that many researchers have paid close attention to. With the increasingly strict requirements of the laws and regulations on the leaching rate of solidified solids and the increase in the construction cost of the landfill, the cost of cement solidification has increased sharply. Adding an appropriate amount of active Al_2O_3, Na_2SiO_3, Na_2CO_3, $CaSO_4$, active husk ash and other salt substances can reduce the amount of cement and effectively reduce the dissolution rate of heavy metals. ZnO in zinc-rich sludge and phosphate in magnesium phosphate cement generate $Zn_3(PO_4)_2 \cdot 2H_2O/Zn_3(PO_4)_2 \cdot 4H_2O$, which changes the orthophosphate environment in the magnesium phosphate cement system and enhances the solidification effect of heavy metals (Zhang et al., 2022). The zinc solidification rate of MgO-cement in zinc-rich sludge is 99.9%, and Zn has little influence on the hydration characteristics of cement, and has good compatibility (Guo et al., 2021).

Table 3
Stabilization/solidification technology of electroplating sludge.

Curing agent	Curing rate	Concentration after treatment (mg/L)	The maximum allowed values	Ref.
CaO	Cr (VI): 99.5%; Fe: 99.6%; Cu: 99.7%; Zn: 98.75%	Cr (VI): 0.001; Fe: 0.054; Cu: 0.003; Zn: 1.352	Cr (VI): 0.1; Cu: 2; Zn:4	Orescanin et al. (2009)
H_3PO_3	Cr: 74%; Fe: 96.2%; Ni: 93.7%; Zn: 96.3%	Cr: 0.024; Fe: 0.495; Ni: 0.043; Zn: 1.393	Cr: 0.5; Ni: 0.4; Zn: 4	Orescanin et al. (2012)
Fly ash (with Al_2O_3)	Cr (VI): 97.9%; Pb: 90.2; Cd: 95.1%	Pb: 1.27; Cd: 0.64; Cr: 0.37	Pb: 5; Cd: 1; Cr: 5	Qian et al. (2009)
Pitch	The curing rate of all ions is greater than 99%.	Cd, Fe < 0.01; Cr, Ni, Zn, Cu < 0.05	Cd: 1; Cr: 5; Pb: 5	Bednarik et al. (2005)
Activated carbon	The leaching rates of TCr, Cu, Ni, Pb and Zn decreased by 35.1, 30.6, 22.3, 23.1 and 22.4%, respectively.	–	Cd: 0.15; Cr: 4.5; Cu: 40; Ni: 0.5; Pb: 0.25; Zn: 100; Hg: 0.05	Lyu et al. (2016)
FeS	The leaching rates of TCr, Cu, Ni, Pb and Zn decreased by 59.6, 100, 63.8, 73.5 and 90.5%, respectively.			
Cement	The curing rate of all ions is greater than 99%.	Cd, Cd, Ni, Pb, Cu < 0.1	Cr: 15; Cd: 1; Ni: 5; Pb: 5	Li et al. (2014a)
Cement	–	Ni: 0.054; Cu: 0.3166; Cr: 3.8875; Cd: 0.0907	Ni: 5; Cr: 5; Cd: 1; Cu、Zn: 100	Shih et al. (2005)

If electroplating sludge is treated with chemicals, the volume of the solidified body can be significantly reduced. Both CaO and phosphate have good curing effects. The heat released by the addition of CaO can destroy organic molecules and produce more stable crystal structures of hydroxide and phosphate. When the mass ratio of CaO to sludge is 1:1, the solidification effect is the best (Orescanin et al., 2009). When the amount of H_3PO_3 is less than 5%, a better curing effect can be obtained (Orescanin et al., 2012). When active substances such as fly ash are added to the lime, the curing effect will be further enhanced (Asavapisit and Chotklang, 2004). Adding Al_2O_3 to fly ash to form ettringite and the Friedel phase is also beneficial to enhance the curing effect (Qian et al., 2009). Alkali-activated blast furnace slag can convert Cr^{6+} into Cr^{3+}, greatly reducing the toxicity of electroplating sludge (Chen et al., 2020). The lime curing method also has the disadvantages of a high curing agent and treatment cost, so it cannot be widely used in small-scale electroplating plants.

In recent years, with the deepening of research, melting curing has developed rapidly. Spinel crystals such as $ZnCr_2O_4$, $ZnFe_2O_4$, $CuFe_2O_4$ and $CuCr_2O_4$ are conducive to the solidification of heavy metals. Iron sludge (Mao et al., 2018a), municipal sewage sludge (Chen et al., 2021), copper sludge (Tang et al., 2014) and electroplating sludge can all be cotreated to achieve a good solidification effect (Fig. 3(a)). At present, SiO_2 is the most important additive for melting and curing, mainly because the lattice network structure provided by SiO_2 can fix heavy metal elements in the glass body, and an appropriate amount of SiO_2 can effectively reduce the melting temperature. $Na_2B_4O_7$ and Na_2SiO_3 can also be used as additives (Aydin and Aydin, 2014). High-temperature pyrolysis is used to treat sludge with high organic content. During the treatment process, the organic matter will be decomposed into short hydrocarbon chain substances, and then recycled as fuel. If the temperature of high-temperature decomposition is high enough, the solid residue can even be vitrified. This treatment method is similar to the melt curing method. However, its energy consumption is high, so its scope of application is greatly restricted.

Other curing agents, such as activated carbon, chelating agents, FeS and asphalt (Bednarik et al., 2005), can also treat electroplating sludge. The mass ratio of FeS to electroplating sludge is 1:5. After 3 days of treatment, the leaching rates of TCr, Cu, Ni, Pb and Zn decreased by 59.6, 100, 63.8, 73.5 and 90.5%, respectively. Chemical precipitation (forming metal sulfide and hydroxide precipitation), iron exchange (forming $CuFeS_2$) and surface complexation are the main mechanisms of FeS removal of heavy metals (Formulas 1-7). The mass ratio of activated carbon to electroplating sludge is 1:2. After 5 days of treatment, the leaching rates of TCr, Cu, Ni, Pb and Zn decreased by 35.1, 30.6, 22.3, 23.1 and 22.4%, respectively. Wang et al. (2023a) used plastic solidified electroplating sludge instead of traditional $CaCO_3$ to produce PVC templates, and found that the performance was greatly improved. Zhong et al. (2007) added chelating agent KS-3 when using cement fine sand as a solidification substrate to treat electroplating sludge containing heavy metals such as Cr and Ni. The toxicity leaching showed that the solidification effect met the standard. Adsorption, electrostatic attraction, surface complexation and chemical precipitation are the main mechanisms for electroplating sludge to fix heavy metals. Solidification treatment is cost-effective and efficient (Fig. 3(b)) (Lyu et al., 2016). Auxiliary solidification methods such as microwave solidification also have great significance and effects on the stabilization/solidification of electroplating sludge (Gan, 2000).

Chemical precipitation: $FeS + H^+ \rightarrow Fe^{2+} + HS^-$ (1)

$$CrO_4^{2-} + 3Fe^{2+} + 4H^- + 4H_2O \rightarrow Cr(OH)_3(s) + 3Fe(OH)_3(s) \quad (2)$$

$$CrO_4^{2-} + 9Fe^{2+} + 6HS^{2-} + OH^- + 10H_2O \rightarrow 2Cr_2S_3(s) + 9Fe(OH)_3(s) \quad (3)$$

$$xCr^{3+} + (1-x)Fe^{3+} + 3H_2O \rightarrow (Cr_xFe_{1-x})(OH)_3(s) + 3H^+ \ (0 < x < 1) \quad (4)$$

$$M^{2+} + HS^- \rightarrow MS(s) + H^+ \quad (5)$$

$$FeS(s) + M^{2+} \rightarrow MS(s) + Fe^{2+} \quad (6)$$

Iron exchange: $xM^{2+} + FeS(s) \rightarrow [(Fe_{1-x}M_x)]S(s) + xFe^{2+} \ (x < 1)$ (7)

where M^{2+} represents Cu^{2+}, Ni^{2+}, Pb^{2+}, and Zn^{2+}.

To solve the problems existing in solidification/stabilization technology, scientific researchers have carried out more research on the mechanism and micromechanism of the solidification/stabilization process of electroplating sludge, to find more economical and effective curing agents, improve the stability of the solidified products and reduce the dissolution of metals. High-efficiency adhesives are the key to solidification/stabilization technology. At present, cement is mostly used as a curing agent, and there is little research on other curing agents. The scope of application of the curing agent and long-term stability of curing body also need to be studied.

Although this technology has a short treatment time and a wide range of applications, it is difficult to find an economic and efficient solidification agent at this stage. The capacity of sludge after solidification is large, and when the pH value is low, harmful elements will also be dissolved and lost again, causing secondary pollution. It is a great waste for electroplating sludge, which can be used as a secondary resource. It does not conform to the 3R principle of solid waste disposal (i.e., reduce, reuse, recycle), and cannot be the main direction for the development of electroplating sludge technology in the future. With the continuous improvement and innovation of various technologies, solidification/stabilization technology will be gradually abandoned, or valuable metals in electroplating sludge will be recycled and then solidified.

4.3. Limiting factors and future development

When one or more substances in cement, quicklime and glass are used to treat electroplating sludge, the leaching concentration of heavy metals will be greatly reduced. Electroplating sludge is difficult to mix evenly with other agents due to its high viscosity, poor dispersibility,

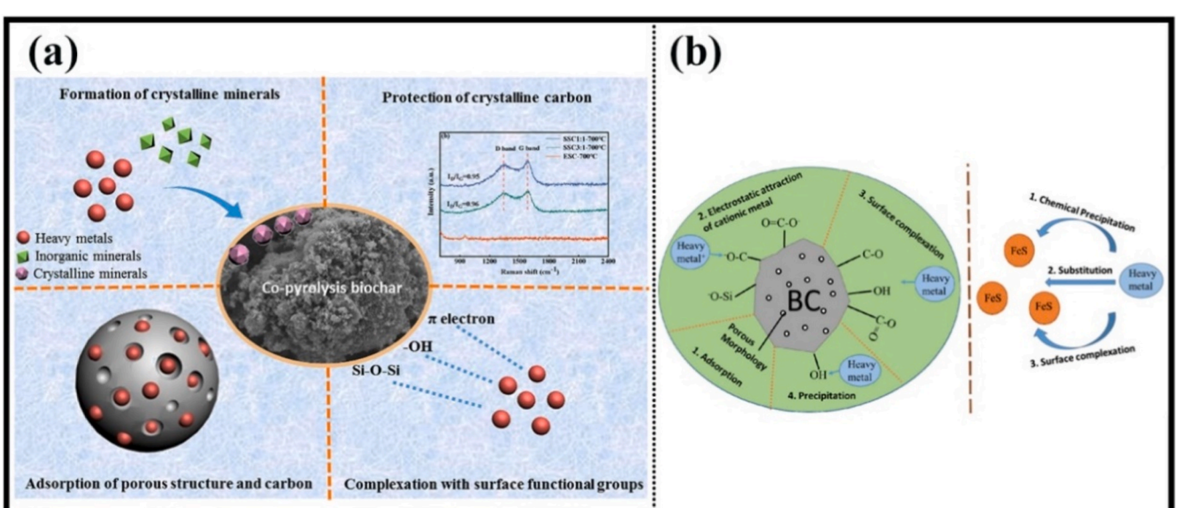

Fig. 3. (a) The immobilization mechanism of heavy metals (co-microwave pyrolysis of electroplating sludge and municipal sewage sludge to synergistically improve the immobilization of heavy metals) (Chen et al., 2021). (b) Mechanisms of heavy metals immobilization by BC and FeS (Lyu et al., 2016).

and uneven particle distribution. Therefore, the pretreatment cost of electroplating sludge is high. In practical applications, cement is generally used for electroplating sludge pretreatment, but the problem of capacity increase is serious. Therefore, it is necessary to research and develop an efficient, economic and stable alkaline agent for electroplating sludge pretreatment so that it can be stored stably for a long time without secondary pollution, and the treatment process or technology should ensure subsequent electroplating sludge reuse.

5. Electroplating sludge reuse

The reduction and pretreatment of electroplating sludge can alleviate the pollution of electroplating sludge, but it still occupies a large amount of land, and there is a risk of secondary pollution. To solve electroplating sludge pollution more thoroughly, it must be reused. The reuse of electroplating sludge includes its use in construction engineering and the production of other high value-added products.

5.1. Cement and concrete

The content of heavy metals in cement raw materials has a significant impact on the formation of crystalline phases in cement production. When using electroplating sludge to partially replace raw materials for cement production, the introduction of heavy metals will promote the formation of tricalcium silicate (C_3S) in cement if the amount of electroplating sludge is less than 15%. However, when the content is higher than this, the high concentration of heavy metals may lead to the transformation of C_3S polymorphism, the decomposition of C_3S, the formation of new compounds and inhibit the crystallization of C_3S in cement (Shih et al., 2005). The form of interference with the crystal phase is still unclear due to the complexity of heavy metals. During the sintering process, about 90% of heavy metals are trapped in the clinkers and cannot be volatilized, but there is no leaching hazard from the sintered clinkers.

Heavy metals in electroplating sludge can also affect the hydration characteristics of composite cementitious materials. Composite cementitious materials can be prepared by mixing cement with electroplating sludge. The amount of electroplating sludge has a direct impact on the water consumption, setting time, mortar fluidity, strength and other indicators of cementitious materials. For example, Cr will accelerate hydration and shorten the initial setting time. Ni and Zn have little effect on the hydration performance and show good compatibility. Therefore, the content of electroplating sludge should not be too high (less than 15%) to prevent the content of heavy metals in cement from exceeding the standard and reducing the strength of cement. In addition, electroplating sludge contains many metal elements, so it can be used as pigment in the preparation of cement-based decorative mortar (Li et al., 2014a, 2014b). Many researchers have studied the toxicity characteristic leaching test (TCLP) of cement mixed with electroplating sludge. The results show that cement has a good solidification effect on heavy metals. Composite cementitious materials pose no threat to the environment (Chen et al., 2012; Sophia and Swaminathan, 2005; Zhang et al., 2021).

It is generally not recommended to introduce electroplating sludge in cement production although some relevant articles have studied the feasibility. The reasons include (1) the volatilization of Zn and Pb; (2) the oxidation of Cr^{3+} and the formation of Cr^{6+} during cement production may affect its long-term environmental performance; (3) the hindrance of cement hydration. Therefore, this study is still in the laboratory research stage. Suitable types of sludge should be selected based on the situation.

5.2. Sintered brick

The use of waste materials instead of clay to produce building bricks has gradually become a focus of attention. Generally, the introduction of electroplating sludge has a certain negative impact on the physical properties of sintered bricks, such as mass loss, bulk density and linear shrinkage, especially leading to a significant increase in water absorption, apparent porosity, specific surface area, pore volume and size. Its microstructure will become rough and porous (Bocanegra et al., 2019; Perez-Villarejo et al., 2015). The pore structure of the brick is one of the most important control factors affecting the leaching rate of heavy metals and mechanical properties. Reducing the pore volume and size will inevitably reduce the release of harmful metals and improve the compressive strength of the brick. Research shows that the type and dosage of electroplating sludge have a significant impact on the properties of bricks. A small amount of aluminum-rich electroplating sludge can improve the mechanical properties of the brick, but excessive use will have a negative impact on the physical and mechanical properties, and the optimal dosage should be less than 8% (Hashim et al., 2022; Zhang et al., 2018a). Increasing the firing temperature and prolonging the firing time are effective methods to reduce the porosity of clay bricks (Dai et al., 2019a; Mao et al., 2019a). During the roasting process, most heavy metals stably enter the spinel phase to achieve effective solidification and reduce environmental risks (Bocanegra et al., 2017). The increase in liquid content in the calcination process also plays an important role in the reduction in pore volume and size. Although increasing the calcination temperature can reduce porosity, it will significantly increase energy consumption. Therefore, adding flux can solve this problem. The addition of fluxes such as waste glass, feldspar and silicate can reduce the melting point of SiO_2 and increase the high-temperature liquid content. Na_2SiO_3 reacts with quartz to form albite, which plays an important role in reducing porosity and water absorption and improving mechanical properties (Dai et al., 2019b). Adding waste glass can also form a glass-ceramic phase and albite and improve the mass transfer and reaction kinetics of spinel formation. The liquid phase fills in the pores to make the bricks compact, which plays an important role in preventing the release of heavy metals. Research shows that waste glass with more than 600 mesh or less than 100 mesh will melt and crystallize into quartz at high temperature, so it is best to add waste glass with approximately 200 mesh (Mao et al., 2018b, 2019b, 2020). Considering its cost, adding waste glass is the best choice at present.

5.3. Glass-ceramics and ceramic materials

Aluminum-rich electroplating sludge can be used to prepare a variety of sludge-based ceramsite with different properties and uses, but it is generally mixed with other substances to prepare in synergy, such as fly ash and coal gangue, to make up for the lack of silicon and aluminum ratio in sludge (Yan, 2011). To meet the physical and chemical properties of ceramsite, its optimum content is generally 10%–30%. In the process of preparing ceramsite, the remaining heavy metals are effectively solidified (Felisberto et al., 2018). The research shows that the addition of additives such as Al_2O_3 and Fe_2O_3 is more beneficial to enhance the curing effect of Cu and Zn, and the addition of SiO_2 is beneficial to inhibit the oxidation of Cr^{3+} and reduce the toxicity (Li et al., 2017). There are many metal oxides in electroplating sludge. The oxide in electroplating sludge can be used as a crystal nucleus to prepare glass-ceramics to realize harmless and material utilization of electroplating sludge (Lin et al., 2021). In the process of heat treatment, there are two steps: nucleation and crystal growth, and temperature is the most important factor (Fig. 4) (Zheng et al., 2023a). The addition of NaOH and other additives can improve the curing rate of Ni, Cr and other metals (Chou et al., 2011). A variety of metals in electroplating sludge, such as Cr, Ni and Pb, are excellent raw materials for the preparation of various colors of pigments. And there is no danger of heavy metal leaching (Milanez et al., 2005; Vilarinho et al., 2021; Li et al., 2015; Matovic et al., 2021; Carneiro et al., 2019; Favero et al., 2022). It can be mixed with red mud and other collaborative preparations to make its color more diverse (Carneiro et al., 2018a, 2018b). However,

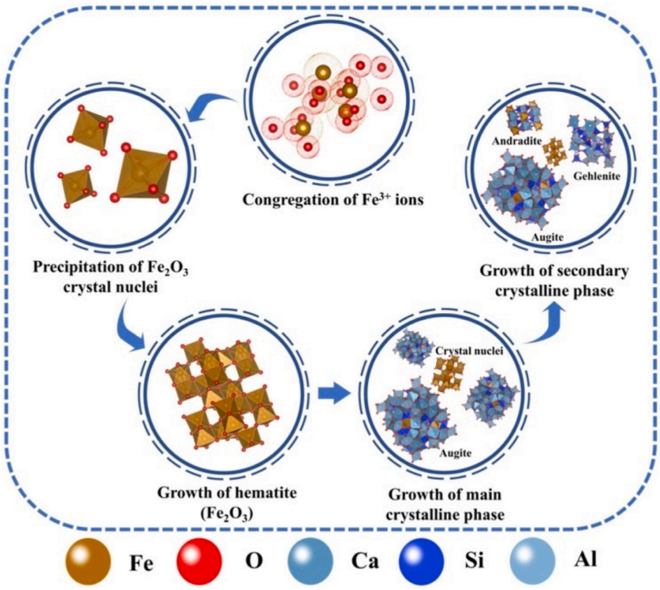

Fig. 4. Schematic diagram of the nucleation and crystal growth behaviors of electroplating sludge-based glass-ceramics (Zheng et al., 2023a).

both ceramics and pigments are currently in the laboratory research stage and have not yet achieved industrial application.

5.4. Adsorption and catalytic materials

Electroplating sludge is suitable for preparing adsorbents. Through physical adsorption, ion exchange and surface complexation, it can effectively adsorb metal ions and dyes in wastewater, as shown in Table 4. The maximum adsorption of Cd^{2+}, Cr^{6+} and Ni^{2+} in water by nonactivated electroplating sludge can reach 37.8 mg/g (Bhatnagar and Minocha, 2009), 288.6 mg/g and 215.4 mg/g (Ramteke and Gogate, 2016), respectively. The removal rate of Zn and Cu is close to 100% when using erdite nanoparticles prepared from iron-containing electroplating sludge to treat heavy metals (Liu et al., 2020), and the adsorption amount of Cr^{6+} can reach 0.33 mmol/g if carbon-based materials are used (Cheng et al., 2021). The removal rate of Ni^{2+} in the electroplating sludge/hydrogen peroxide system can reach 87% (Fig. 5(a)) (Peng et al., 2020b). The adsorption capacity of electroplating sludge-based adsorbents is much higher than that of coal-based activated carbon, ion exchange resins and other common adsorbents. Therefore, electroplating sludge can be directly used for electroplating wastewater treatment before being treated as hazardous waste. Research shows that calcined electroplating sludge may have better adsorption than the original electroplating sludge (Fig. 5(b)) (Peng et al., 2020a; Tran et al., 2021). In addition, electroplating sludge has great potential in treating dye (Yang et al., 2021; Netpradit et al., 2004) and liquid fuel pollutants (Fig. 5(c)) (Kabtamu et al., 2020; Huang et al., 2021b).

Electroplating sludge can also be used to prepare catalysts. The structure of electroplating sludge is regulated by the MOF synthesis method so that it has a large number of carboxyl and polymetallic catalytic centers, and a denitrification catalyst with high catalytic activity (99.99% activity at 350 °C) can be prepared (Ma et al., 2021). The magnetic copper-containing catalyst prepared from electroplating sludge can be used for the catalytic modification of biobased FFRs in a hydrogen atmosphere (Xiao et al., 2022a). The Zn–Cr spinel catalyst prepared from electroplating sludge can be used for the catalytic hydrogenation of CO_2 to produce methanol (Hou et al., 2022a). In addition, the catalyst can also be used for electrocatalytic reduction of N_2 to produce ammonia (Li et al., 2022b), electroreduction of CO_2 to produce HCOOH (Zhong et al., 2022), selective catalytic reduction of NO (the NO removal rate is 99.7%) (Zhang et al., 2014, 2018b; Shen et al., 2020), catalytic oxidation of VOC (Bai et al., 2021), photocatalytic degradation of dyes (Fig. 5(d)) (Cao et al., 2017; Golban et al., 2018), photoreduction of CO_2 (Song et al., 2021), etc. It provides help to reduce air pollution and water pollution and realizes high value-added utilization of electroplating sludge. This is due to the presence of a variety of transition metals in electroplating sludge. If the electroplating sludge is modified, the catalytic activity can be enhanced.

5.5. Alloy materials

Pyrometallurgical treatment of electroplating sludge produces less harmful residues compared with hydrometallurgy. The valuable metals in sludge are reduced by reducing carbon and recycled into alloy ingots, while the remaining harmful elements are solidified in the form of stable spinel phase or vitrified slag. Generally, chromium-containing sludge, iron-containing sludge, and copper-containing sludge are treated with this method to produce alloys that can be used as raw materials for stainless steel, while the slag is used for the preparation of harmless building materials. Table 5 lists the elemental purity of some alloy

Table 4
Electroplating sludge based adsorbent and its treatment effect.

Sludge type	Target	Treatment effect	Main removal mechanism	Ref.
RES and CES	Ni^{2+} in electroplating wastewater	The adsorption capacity of RES and CES for Ni^{2+} is 135.7 and 118.3 mg/g, respectively.	Surface complexation and ion exchange	Peng et al. (2020a)
ES/H_2O_2 system	Nickel citrate	87% of total Ni^{2+} removed within 50 min.	Surface complexation	Peng et al. (2020b)
Chromium sludge (hydrothermal treatment)	Dibenzothiophene in liquid fuel	The adsorption capacity of hydrothermal synthetic adsorbent containing HF is 40.11 mg/g.	Metal-sulfur interaction; High surface area and high porosity	Kabtamu et al. (2020)
Iron sludge	Zn^{2+} and Cu^{2+} in water	The removal rate of Zn^{2+} and Cu^{2+} is close to 100%.	Surface complexation	Liu et al. (2020)
Mixed sludge	Cd^{2+} in water	The maximum adsorption capacity is 37.8 mg/g.	–	Bhatnagar and Minocha (2009)
Modified sludge	Cu^{2+} and Cr^{6+} in water	Maximum values being 288.6 and 215.4 mg/g for Cu^{2+} and Cr^{6+}, respectively.	Surface complexation	Ramteke and Gogate (2016)
Iron-modified sludge-based hollow-structured porous carbon	Cr^{6+} in water	The highest adsorption capacity was 0.33 mmol/g.	Physical adsorption, electrostatic attraction, redox, chelation and doping adsorption	Cheng et al. (2021)
RES and CES	Cu^{2+} in water	The maximum adsorption capacity of CES and RES is 92 mg/g and 76.34 mg/g, respectively.	Ion exchange	Tran et al. (2021)
Iron sludge	Colourant	The maximum adsorption capacity of red ink is 34.48 mg/g.	–	Netpradit et al. (2004)
Zinc sludge	Mixed dye	The adsorption rate of methylene blue, Rhodamine B and Congo red is higher than 80%, and the removal rate is still higher than 75% after five recoveries.	Low carrier recombination rate and electron transfer resistance, good photocatalytic effect	Huang et al. (2021b)

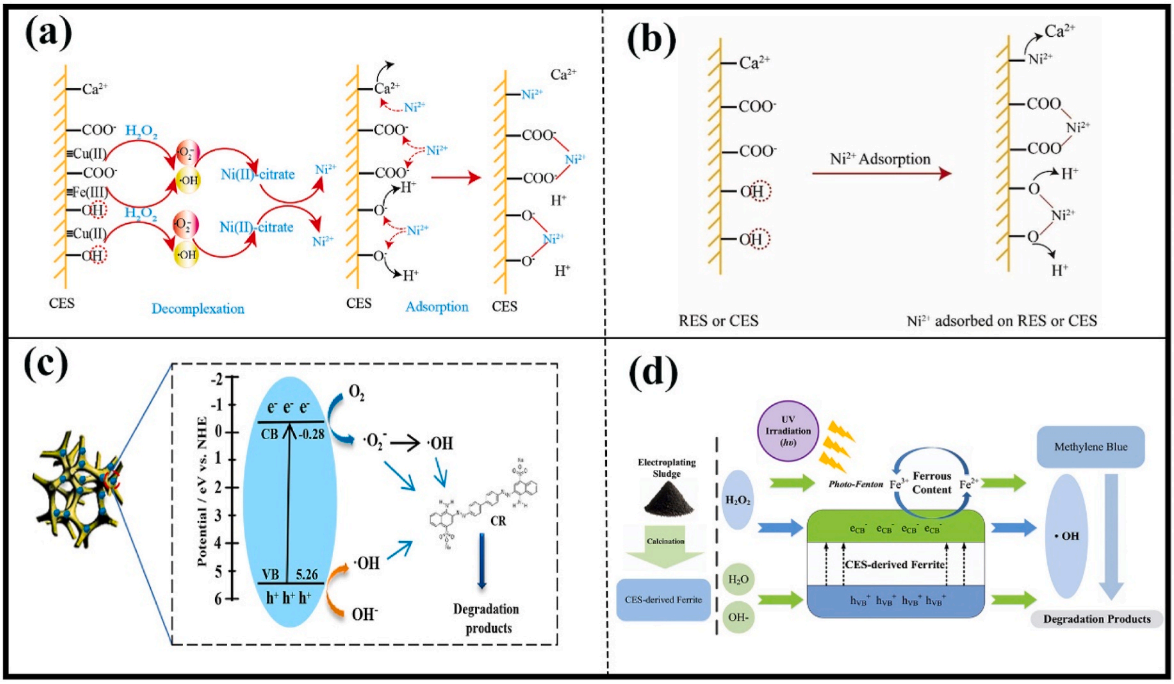

Fig. 5. Schematic illustration of (a) Ni^{2+}-citrate removal by calcined ES/H_2O_2 (Peng et al., 2020b). (b) Ni^{2+} adsorption on ES (Peng et al., 2020a). (c) The photodegradation process of Congo red over LC/h-ZIF-8 (electroplating sludge based photodegradation agent) (Huang et al., 2021b). (d) Electroplating sludge-derived zinc-ferrite catalyst for the efficient photo-Fenton degradation of dye (UV/CES/H_2O_2 system) (Cao et al., 2017).

Table 5
Purity of electroplating sludge - based alloy materials.

Alloy type	Fe/%	Cr/%	Cu/%	Ni/%	Si/%	C/%	S/%	Ref.
Fe–Cr–Si	31.61	31.78	–	–	36.59	0.01	0.01	Wang et al. (2022e)
Cu–Ni–Fe	75.21	4.67	8.73	9.42	–	–	–	Yu et al. (2021a)
Fe–Cr–Si	21.7	36.0	–	–	42.3	0.01	0.009	Wang et al. (2023b)
Cu–Fe	8.0	–	87	–	–	–	–	Zheng et al. (2023b)
Ni–Fe	4.05	–	–	95.70	–	–	0.029	Wang et al. (2019)
Fe–Cr–Si	50.1	16.7	–	–	32.4	0.01	0.008	Wang et al. (2023c)
Copper matte	0.04	–	83.55	–	–	–	16.41	Wang et al. (2021b)

materials. Nowadays, the carbon thermal reduction process also faces many challenges, such as low metal recovery rates and difficulty in controlling the carbon and sulfur content of the alloys produced. For chromium alloys, Cr_2O_3 reacts with MgO and FeO at high temperatures to form stable spinel phases, which inhibits the reduction of Cr_2O_3 (Yu et al., 2021a). Cr_2O_3 can also react with C to generate Cr_3C_2. The high melting temperature of Cr_3C_2 makes it difficult to separate from the slag, resulting in poor fluidity of the slag and loss of metal Cr. Therefore, the recovery rate of Cr using a carbon thermal reduction method is usually not high (75–85%). On the other hand, carbothermal reduction can introduce excessive carbon into the alloy. Other types of alloys also face similar problems.

Another important challenge is the presence of $CaSO_4$ in electroplating sludge. $CaSO_4$ will be reduced to CaS by the reducing substance and a large amount of sulfur (an element harmful to steel) will be introduced into the alloy (Wang et al., 2021b). High-sulfur alloys cannot be used for stainless steel production. Meanwhile, solid CaS will precipitate from the slag due to the low solubility of CaS in oxide melts. Deteriorates the fluidity of the slag. Therefore, sludge containing $CaSO_4$ is difficult to be treated by pyrometallurgical method. To address this issue, researchers have proposed a two-stage carbon thermal reduction process that utilizes high-temperature calcination for pre-desulfurization. $CaSO_4$ in sludge decomposes into SO_2 during the roasting process, and the desulfurized sludge is reduced with ferrosilicon at 1600 °C to obtain a low sulfur and low-carbon Fe–Cr–Si alloy. Si is a strong reducing agent that can easily reduce Cr_2O_3 to metal, improving the recovery rate of Cr. Therefore, the silicon thermal reduction process can improve the recovery of Cr, while the SiO_2 generated acts as a glass slag. Finally, Fe–Cr–Si alloy with low sulfur and carbon contents was obtained, with a Cr recovery rate of 98.62% (Wang et al., 2022e, 2023b). The addition of CaO also helps to reduce the viscosity of slag, thereby reducing metal loss by improving the efficiency of slag metal separation. In addition, co-treatment of multiple solid waste and electroplating sludge to achieve wastes treatment is also a promising way to prepare alloys and extract heavy metals (Yu et al., 2021a; Zheng et al., 2023b; Xiao et al., 2022b).

5.6. Other applications

Electroplating sludge contains a variety of transition metal elements, so it can also be used to prepare oxygen carriers (Han et al., 2022), amorphous nickel hydrogen carbonate electrode materials with excellent supercapacitor performance (prepared by simple hydrothermal reaction) (Hou et al., 2022b), ferrite materials (Chen et al., 2010; Lin et al., 2020), etc. However, the promotion and application of hese technologies are severely limited due to the scattered origin of electroplating sludge, the great difference in its composition, the complex process of producing high value-added materials, and the limited research on the solidification mechanism of some heavy metal ions. In addition, the market demand for these products is insufficient, and secondary pollution may be related to these products, which also limits their industrialization.

6. Conclusions and prospects

6.1. Conclusions

The treatment of electroplating sludge has become an obstacle to the sustainable development of the electroplating industry due to its inherent harmfulness. The reduction treatment of electroplating sludge cannot reach economic and technical feasibility at the same time. The main limitations include the large difference in the composition of electroplating sludge and the high water content caused by inefficient filtration equipment. At present, more attention is being paid to the pretreatment and reuse of electroplating sludge, but the existing methods have difficulty achieving industrialization and large-scale electroplating sludge treatment or reuse. The main reasons limiting its pretreatment include high treatment cost, secondary pollution, high concentration of heavy metals reducing the long-term stability of sludge, etc. The main reasons restricting its reuse include secondary pollution, imperfect pretreatment, imperfect policies, low activity of electroplating sludge, low added value of related products, insufficient product market, and long transportation distance. It is worth noting that the lack of electroplating sludge pretreatment and related product standards also seriously restricts the pretreatment and reuse of electroplating sludge. Therefore, reasonable treatment and disposal of electroplating sludge requires assistance from many parties, and there are still many problems to be solved.

6.2. Prospects

Although researchers have paid much attention to the reduction, pretreatment and reuse of electroplating sludge, there are still some deficiencies. Based on the current research status and market factors of electroplating sludge, our suggestions for electroplating sludge treatment are as follows:

(1) Ideological reconstruction. Systematically consider the electroplating sludge ecosystem, which is a complete process of "electroplating process - electroplating sludge treatment - recycling". The large-scale secondary application of electroplating sludge should combine the production process, characterization and analysis of physical and chemical properties, and pretreatment technology of electroplating sludge. The most important thing is to establish an electronic database of the physical and chemical properties of electroplating sludge to achieve accurate understanding and macrocontrol to address and reuse targets. In addition, the products produced should have no secondary harm to the ecological environment. Nonreusable sludge shall be pretreated.

(2) Technological innovation. Electroplating sludge treatment needs to combine a whole set of technologies, because a single treatment technology cannot solve the problems related to electroplating sludge. For the electroplating industry, the research and introduction of technologies and equipment, such as cleaner production and high-efficiency filter press, should be accelerated to reduce the amount and toxicity of electroplating sludge. It can also improve the automation and informatization level of the disposal process through multiprocess integration innovation. In combination with the relevant industrial chain of electroplating sludge, it is necessary to develop a new market for large-scale comprehensive secondary utilization of electroplating sludge, and accelerate the research of industrialization technologies and key technologies such as efficient dispersion, moisture reduction, heavy metal stabilization/solidification, and activation of electroplating sludge. The most important thing is to find a suitable curing agent that can reduce volume and is inexpensive.

(3) Policy support. Electroplating operations and electroplating sludge consumption should be coordinated and unified. In combination with local realities, the regulations on comprehensive utilization of electroplating sludge and pollution prevention should be more complete and comprehensive. It is very important to improve the toxicity identification and evaluation standards of electroplating sludge, formulate technical specifications for electroplating sludge disposal, and develop relevant product standards and technical feasibility guidelines.

(4) Market supervision. Various measures should be taken to stimulate the market potential of electroplating sludge related products according to local conditions. According to the areas where electroplating sludge is produced, the research and promotion of electroplating sludge related products can be accelerated. It is important to develop and promote the large-capacity, high value added and multichannel disposal mode of electroplating sludge to promote electroplating sludge related products to the public.

Credit authors statement

Huimin Wang: Investigation, writing - editing. **Xiaoming Liu:** Conceptualization, resources, writing - review & editing, supervision. **Zengqi Zhang:** Conceptualization, resources, writing - review & editing, supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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