

Review

Wastewater Treatment in Mineral Processing of Non-Ferrous Metal Resources: A Review

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Abstract: Water used by mining enterprises needs to be comprehensively recovered and utilized to achieve clean production. This requires the effective treatment of mineral processing wastewater. Wastewater produced during non-ferrous metal mineral processing contains a complex mixture of pollutants at high concentrations, making comprehensive treatment difficult. Here, the sources of and hazards posed by wastewater produced during non-ferrous metal mineral processing are introduced and the techniques for removing heavy metal ions and organic chemicals are reviewed. Chemical precipitation and adsorption methods are often used to remove heavy metal ions. Chemical precipitation methods can be divided into hydroxide and sulfide precipitation methods. Organic chemicals are mainly removed using oxidation methods, including electrochemical oxidation, photocatalytic oxidation, and ultrasonic synergistic oxidation. External and internal cyclic utilization methods for treating wastewater produced by mineral processing plants are introduced, and a feasibility analysis is performed.

Keywords: cyclic utilization; mineral processing; non-ferrous metal; wastewater treatment



Citation: Meng, S.; Wen, S.; Han, G.; Wang, X.; Feng, Q. Wastewater Treatment in Mineral Processing of Non-Ferrous Metal Resources: A Review. *Water* **2022**, *14*, 726. <https://doi.org/10.3390/w14050726>

Academic Editor: Andrea G. Capodaglio

Received: 16 January 2022

Accepted: 22 February 2022

Published: 24 February 2022

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1. Introduction

Water is a basic natural resource and is essential to humans. Water resources are essential to almost all human activities and have various utilization values. Water resources must be adequate to meet the demands of economic (including scientific and technical), social, and domestic activities, and the environment [1–4]. Water demand has increased in recent decades due to population growth and industrial development. Many parts of the world are now in a state of water crisis exacerbated by water resource mismanagement [5]. Science-based water resource management is important for resolving water supply crises. The recycling and reutilizing of wastewater is generally acknowledged as being key to achieving sustainable water resource management. The natural purification of wastewater has disadvantages [6], such as requiring a long time period, being markedly affected by climate change, and having poor efficiency; therefore, it is important to develop efficient methods for treating and recovering wastewater.

Since the industrial era started, mining has led to rapid development, but also to many environmental problems, such as the pollution of air [7], soil [8–10], lakes [11], and the oceans [12], and the destruction of ecological systems [13,14]. Mineral processing wastewater produced at mining sites is an important source of environmental pollution. Mineral processing consumes large amounts of water and produces large amounts of wastewater, which accounts for 10% of total industrial wastewater around the world [15]. Mineral processing wastewater usually contains various heavy metal ions (e.g., Cd^{2+} , Cu^{2+} , Pb^{2+} , and Zn^{2+}), fine suspended solids, organic chemicals, and other pollutants that pose serious risks to the environment [16–19]. Non-ferrous metal mineral processing produces

wastewater containing large amounts of various heavy metals, fine suspended solids, and organic chemicals due to the complex compositions of the minerals, the beneficiation processes applied, and the reagents used.

Fine suspended solids in non-ferrous metal mineral processing wastewater are generally removed through natural settling, flocculation and subsequent settling, and membrane separation [20]. The complex compositions of ores and the mineral processing methods used cause the wastewater produced to contain large amounts of heavy metal ions and organic chemicals. Removing organic chemicals and heavy metal ions is key to reutilizing non-ferrous metal mineral processing wastewater. Many techniques have recently been developed for removing heavy metal ions from wastewater, including chemical precipitation [21,22], adsorption precipitation [23–30], ion exchange [31,32], membrane separation [33–35], flocculation precipitation [36–38], and combined oxidation/coagulation [39], from which remarkable results have been found. These methods can effectively remove heavy metal ions from wastewater, and could be used to remove heavy metal ions from non-ferrous metal mineral processing wastewater. Most organic pollutants (e.g., sodium xanthate) in wastewater are difficult to remove using conventional treatment methods such as coagulation [40], adsorption [41], ion exchange [42], and chemical oxidation [43]. Efficient methods have been developed for removing organic pollutants from wastewater, including Fenton oxidation [44], electrochemical oxidation [45–48], and photocatalysis [49–51]. These methods could be used to remove common organic pollutants (e.g., xanthate) from non-ferrous metal mineral processing wastewater.

In this review, the sources of wastewater from non-ferrous metal mineral processing and its potential hazards, including heavy metal ions and residual flotation reagents, are introduced. Recent research progress on the treatment of heavy metal ions and residual reagents in wastewater from non-ferrous metal mineral processing is discussed. Furthermore, current approaches for the recycling of flotation wastewater from non-ferrous metal mineral processing are introduced.

2. Wastewater Sources and Hazards in Non-Ferrous Metal Mineral Processing

2.1. Wastewater Sources in Non-Ferrous Metal Mineral Processing

The different components of ore have different physical and chemical properties. Mineral enrichment can be achieved using one or more methods (e.g., flotation separation, electrical separation, gravity concentration, and magnetic separation), depending on the characteristics of the raw ore. Gravity concentration, electrical separation, and magnetic separation processes do not usually require reagents to be added, therefore, the wastewater can be recycled without treatment or after a simple settling treatment. Flotation wastewater includes wastewater from the flotation process (which contains a complex mixture of reagents) and wastewater from other processes, and, consequently, requires various treatments.

Wastewater from the flotation process includes tailing wastewater, concentrate wastewater, and raw ore washing water. Concentrate wastewater comprises the overflow water and filtered water produced during the concentrate dehydration process. This wastewater contains many flotation reagents, heavy metal ions, and suspended solids, which are generally difficult to remove. Tailing wastewater mainly comprises the overflow water and filtered water produced during the tailing dehydration process, and accounts for a large proportion (generally 50–70%) of the total wastewater produced at a processing plant. The raw ore must be flushed and deslimed if the mud content is too high, and the water used cannot be recycled without being treated.

Other types of wastewater are equipment water, wet dust removal equipment drainage water, ground flushing water, and wastewater from open pit mines. Equipment water comprises equipment cooling water and equipment shaft sealing water, including crushing water, high-pressure roller-grinding water, grinding equipment cooling water, and pulp pump shaft sealing water. Water produced by dust-cleaning equipment is discharged from the crushing and screening system and the belt conveying system. Ground washing

water from mineral processing workshops includes water from crushing and screening workshops, grinding workshops, and flotation workshops and mainly contains ore particles, flotation agents, and oil. The ore that accumulates in areas exposed to the open air for a long time period will be washed by natural rain. Mineral processing wastewater contains many types of sludge and mineral particles. The specific sources of mineral processing wastewater are summarized in Table 1.

Table 1. Sources of mineral processing wastewater.

| Category | Source |
|-----------------------|---|
| Processing wastewater | 1. Concentrate wastewater 2. Tailing wastewater 3. Ore flushing water |
| Other wastewater | 1. Equipment with water 2. Drainage of wet dust cleaning apparatus 3. Floor flushing water 4. Mine acid wastewater |

2.2. Wastewater Hazards from Non-Ferrous Metal Mineral Processing

2.2.1. Hazards Posed by Heavy Metal Ions

The diversity of minerals in non-ferrous metal ore determines the variety and relatively high content of heavy metal ions in wastewater from mineral processing. Heavy metals are non-biodegradable inorganic pollutants that are difficult to remove from wastewater [52–54]. Therefore, heavy metals in wastewater discharged into the environment will readily accumulate in soil and water [55,56], and can affect humans. Heavy metal pollution occurs more rapidly, and becomes more widespread in water than soil due to the fact that water flows, taking heavy metals with it. Heavy metal pollution, therefore, has more serious environmental effects in water than soil. A certain degree of heavy metal pollution of water will endanger the aquatic ecosystem [57–60], and water polluted with heavy metals will have many adverse effects on aquatic plants and animals (Table 2).

Table 2. Hazards of heavy metal pollution to aquatic organisms.

| Contaminated Organism | Specific Hazards |
|-----------------------|--|
| Aquatic plants | 1. Decreasing photosynthesis 2. Inhibiting plant growth 3. Causing plant atrophy and death |
| Aquatic animals | 1. Causing metabolic disorders 2. Causing organ damage 3. Altering genetic information |

The potential hazards of water polluted by heavy metals to humans are also of great importance. It is possible for humans to directly drink contaminated water, touch water contaminated by heavy metals on their skin, or consume food contaminated by heavy metals through the food chain (Figure 1) [57–60]. Although some metals are necessary for human health, the body only tolerates very low levels, while elevated levels can be harmful [61]. Heavy metals, such as Pb, Cd, and Cr are of low value in human health functions, and are also harmful to human health when trace amounts are present in the body [62,63]. When heavy metals enter the body, they are deposited in the vital organs, such as the brain, kidneys, and stomach, and can eventually lead to illness and even death [64,65].

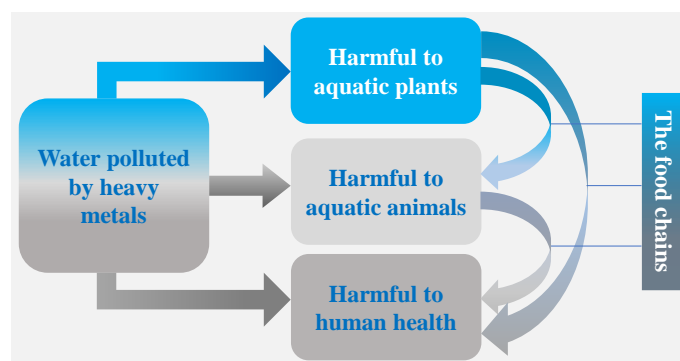


Figure 1. Potential hazards of heavy metals in water to biota.

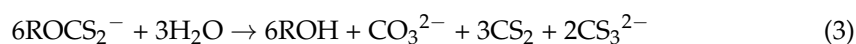
2.2.2. Hazards Posed by Reagent Residues

The chemical oxygen demand (COD), which is the oxygen equivalent that can be used by substances (generally organic) that, in turn, can be oxidized by a strong oxidant in water, is an important index of water quality [66]. The COD is an important parameter relating to organic pollutants, which is useful when studying river pollution and industrial wastewater and when operating and managing wastewater treatment plants. The COD can be determined rapidly. Persistent organic pollutants in industrial wastewater can have various negative effects on the environment. Some persistent organic pollutants can cause odor problems, pose risks to aquatic organisms, occur at saturated concentrations in soil, affect soil quality, discolor natural water, cause surface water eutrophication, and pollute surface layer water [67–69]. If not removed, many organic pollutants can adsorb to sediment and be deposited on river and lake beds, which can result in them having long-term toxic effects on aquatic biota. A river ecosystem will be destroyed if a large proportion of the aquatic biota dies. Humans that consume aquatic organisms from polluted water can absorb many toxins that can accumulate in the body. Some of these toxins may be carcinogenic or mutagenic, and therefore pose great risks to health. If polluted river water is used for irrigation, the plants and crops may be affected by the pollutants and may suffer poor growth.

Almost 2×10^9 t of minerals (including ores of almost all non-ferrous metals, e.g., sulfide and oxide ores of copper, lead, and zinc) are processed by flotation each year around the world [66]. Organic collectors and regulators are widely used when non-ferrous metal ores are subjected to the flotation process [70] to achieve reasonable separation and ensure that the processing plants are economically effective. However, organic reagents used in the flotation process cannot be completely recovered, and reagent residues can enter the thickener with the washing water and subsequently enter the mineral processing wastewater. Organic reagents in wastewater from non-ferrous metal mineral processing plants can undergo various reactions to form products that are more harmful than the original reagents to the environment. For example, xanthate is a common collector used in non-ferrous sulfide ore flotation processes [70]. Xanthate can undergo various degradation reactions in wastewater at different pH values [71]. At acidic pH values, xanthate can undergo two degradation reactions, xanthogenate hydrolysis and xanthic acid decomposition, as shown below:

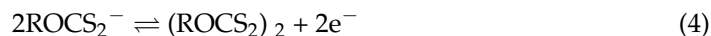


At alkaline pH values, xanthogenate can undergo the hydrolysis reaction shown below:



Trithiocarbonate (CS_3^{2-}) produced in this reaction can decompose to form CS_2 and S^{2-} .

Xanthate is sensitive to oxygen and undergoes the oxidation reactions shown below:



The production of $(\text{ROCS}_2)_2$ will greatly increase the COD of wastewater, and this will increase the difficulty involved in treating the wastewater. CS_2 produced through xanthic acid decomposition is toxic to humans because it can disrupt normal metabolism in cells and interfere with lipoprotein metabolism, resulting in vascular lesions, neuropathy, and damage to the main organs.

3. Wastewater Treatment in Mineral Processing of Non-Ferrous Metals

3.1. Treatments for Heavy Metal Ions in Wastewater

Some metal oxides [72], carbon materials [73], biomass [74], and polymers [24] have been used to remove heavy metals from wastewater because they are cheap, have high adsorption efficiencies, are recyclable, and are very environmentally compatible. Adsorbents based on these materials can remove heavy metal ions through chemical reactions (e.g., coordination, ion exchange, oxidation–reduction, or precipitation) and physical interactions (e.g., electrostatic attraction, hydrogen bonding, or surface complexation).

3.1.1. Chemical Precipitation

Chemical precipitation has been widely used to remove heavy metal ions from wastewater [75]. The chemical reagent reacts with heavy metal ions in wastewater to form insoluble precipitates [76]. The precipitates can then be removed from the wastewater using settling or filtration techniques. Chemical precipitation methods can be divided into hydroxide and sulfide precipitation methods. Hydroxide precipitation is economically viable, and many hydroxides have been used to precipitate metals from wastewater. Giannopoulou et al. [77] removed Ni from wastewater using a hydroxide method. When NaOH was added to wastewater containing Ni, the Ni precipitated as $\text{Ni}(\text{OH})_2$. The Ni removal efficiency was 99.76% at pH 10. After reducing Cr (VI) to Cr (III) using ferrous sulfate, $\text{Ca}(\text{OH})_2$ or NaOH can be added to the precipitate and remove the Cr (III) from the wastewater (Figure 2) [75]. Adding a flocculating agent such as alum, a ferric salt, or an organic polymer to wastewater can accelerate precipitation [78]. The pH of the solution affects the precipitation of heavy metal ions into hydroxides. Various metal hydroxides are soluble in a narrow pH range, so heavy metals can be removed from the wastewater at a low cost using an appropriate pH and chemicals that are easy to treat.

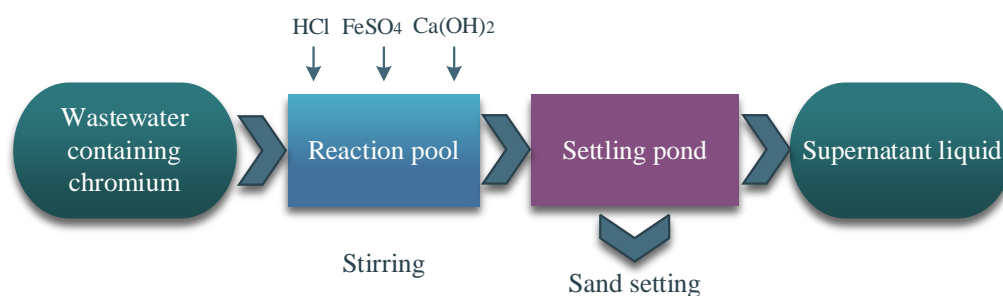
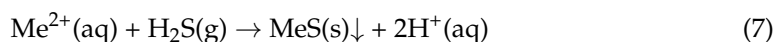
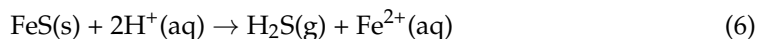


Figure 2. Schematic of Cr removal by $\text{Ca}(\text{OH})_2$ precipitation.

Hydroxide precipitation is generally suitable for treating industrial wastewater containing heavy metals at high concentrations as simple mixtures. However, hydroxide precipitation has some problems, including producing a large amount of low-density sludge that is difficult to dehydrate, and the pH-influenced precipitation reagent releasing metal ions into the solution. Sulfide precipitation is also effective for removing heavy metal ions from wastewater. Metal sulfide precipitates are markedly less soluble than hydroxide precipitates. Metal ions can be quickly and selectively removed as sulfide precipitates.

The main reactions involved in sulfide precipitation are between H_2S and metal ions, as shown below [79]:



Metal sulfide sludge produced through sulfide precipitation settles faster and is treated more easily than sludge produced through hydroxide precipitation. However, there are some problems with the sulfide precipitation method, including that acidic conditions cause H_2S (which is toxic) to be produced. Sulfide precipitation, therefore, needs to be performed in a neutral or alkaline medium. Some examples of removal of metal ions by chemical precipitation are shown in Table 3.

Table 3. Chemical precipitation methods for removing heavy metals from wastewater.

| Process | Removing of Metal Ions | Chemicals/Adsorbents Used | Removing (%) / Q_{\max} | Experimental Conditions | References |
|-------------------------|----------------------------------|-------------------------------|---------------------------|--|------------|
| Hydroxide precipitation | $\text{Cu}^{2+}, \text{Zn}^{2+}$ | Apatite | >90 | $\text{Ca}_5(\text{PO}_4)_3$ $\text{F}/\text{Ca}_5(\text{PO}_4)_3(\text{OH}) = 1:6$ | [80] |
| | Cu^{2+} | CaO + biosorption | >99 | $\text{pH} = 12.5$ | [76] |
| | Zn^{2+} | CaO | >99 | In the pH range of 9 to 10 | [81] |
| | Ni^{2+} | NaOH | >99 | $\text{pH} = 10.0$ | [77] |
| | $\text{Cu}^{2+}, \text{Zn}^{2+}$ | CaO | >99 | In the pH range of 7 to 11 | [82] |
| | Cr^{3+} | CaO and MgO | >99 | $\text{pH} = 8.0$ | [83] |
| Sulfide precipitation | $\text{Cu}^{2+}, \text{Zn}^{2+}$ | H_2S | >90 | $\text{pH} = 3.0$ | [84] |
| | Hg^{2+} | Pyrrhotite and pyrite | >90 | $\text{pH} = 4.0$ | [85] |

3.1.2. Ion Exchange

In the ion exchange method, harmful ions are removed from wastewater using an ion exchange material that can adsorb, bond, and exchange the ions. Ion exchange has been used to remove heavy metal ions from industrial wastewater due to the high capacities, high removal efficiencies, and other advantages of ion exchange materials [86,87]. Ion exchange materials can be classed as inorganic (e.g., zeolites [88]) or organic (e.g., ion exchange resins [89]). Cation exchange resins can be divided into strong acidic cationic resins containing sulfonic acid groups, and weak acidic cationic resins containing carboxylic acid groups. H^+ in sulfonic acid or carboxylic groups in the cation exchange resin are exchanged for heavy metal ions in the solution being treated [90]. Both organic and inorganic ion exchange materials have limitations. Organic ion exchange resins are poorly thermally stable [91]. For example, the mechanical strengths and heavy metal removal abilities of ordinary organic ion exchange resins tend to be lower at high temperatures (e.g., for treating liquid radioactive waste) than at lower temperatures [92]. Inorganic ion exchange materials are poorly reusable, have low mechanical strengths, and are not resistant to some chemicals [93]. Inorganic–organic composite ion exchange materials have been developed to attempt to overcome these limitations of organic ion exchange resins and inorganic adsorbents [94]. Composite ion exchange materials combine the mechanical properties of organic polymers and the inherent properties of inorganic compounds, meaning they have advantageous mechanical properties, are chemically inert, are stable at high temperatures and when exposed to radiation, and can reproducibly and selectively remove heavy metal ions from solution [95–101]. Some examples of composite ion exchange materials are shown in Table 4.

Table 4. Sodium ion exchange capacities of composite ion exchange materials.

| Composite Materials | Thermal Stability (°C) | IEC for Na Ions | References |
|---|------------------------|-----------------|------------|
| n-Butylacetatezr (IV) iodate | 200 | 0.78 | [102] |
| Polyaniline Ti (IV) tungstate | 300 | 0.78 | [103] |
| Zirconium (IV) iodotungstate | 400 | 0.68 | [104] |
| Poly-orthotoluidine Zr (IV) iodate | 100 | 0.85 | [105] |
| Zirconium (IV) molybdo tungsto-vanadosilicate | 100 | 0.86 | [106] |
| Polyaniline Zr (IV) molybdophosphate | 200 | 1.30 | [107] |

3.1.3. Adsorption

The adsorption method has great potential because the adsorbents that are used are cheap, the method is simple, and the adsorbents used can remove heavy metals from wastewater even at low concentrations [108]. The most common materials used to adsorb heavy metals from wastewater are activated carbon, polymers, and nanomaterials. These materials all have three characteristics [109], as follows: (i) a chemical structure containing chelating sites or ion exchange groups that can interact with heavy metal ions; (ii) a hydrophilic and three-dimensional network structure, providing a large area in contact with water; and (iii) low cost and availability from a wide range of sources. However, commercially available activated carbon can only be used at a large scale because it is expensive to produce and reuse [110]. Polymers and nanomaterials have therefore been used to remove metal ions from wastewater in many studies.

Polymers are particularly suitable adsorbents for removing metal ions from wastewater because they have high specific surface areas, are cheap to reuse, and are environmentally compatible [111–114]. However, polymer adsorbents have low adsorption capacities and poor selectivities, and need to be modified for practical use [115]. El et al. [115] synthesized a novel hyper-cross-linked nanoscale chelating resin with a high specific surface area (335 m²/g) and a mesoporous structure (2.882 nm diameter pores). At room temperature (25 °C), the adsorption capacities of the hyper-cross-linked nanoscale chelating resin for Pb, Cd, and Zn ions were 1.2 mmol/g (at pH 5.5), 1 mmol/g (at pH 6.0), and 0.9 mmol/g (at pH 6.3), respectively, which are much higher than the adsorption capacities of many other adsorbents. Ulusoy et al. [116] directly polymerized polyacrylamide in a suspension of bentonite and zeolite to produce a polyacrylamide–bentonite/zeolite composite material. At room temperature (25 °C) and pH 4.5, the adsorption capacity of the polyacrylamide–bentonite/zeolite for Pb (II) was 0.16 mmol/g. The adsorption capacities of the modified polymers used in previous studies as adsorbents for some metal ions in wastewater are summarized in Table 5.

Nanomaterial adsorbents are important for removing heavy metal ions from wastewater. Many nanoscale metal oxides, such as nano-alumina, nano-cerium oxide, nano-iron oxide, nano-magnesium oxide, nano-manganese oxide, and nano-titanium oxide, have been found to be promising adsorbents for removing heavy metal ions from aqueous solutions. Nano-oxide particles with certain characteristics (including a small volume, large specific surface area, and strong magnetism) have been found to strongly adsorb heavy metals [122–124]. Fang et al. [125] synthesized a puffed rice carbon with coupled sulfur and metallic iron composite nanomaterial that efficiently adsorbed Hg²⁺ from an aqueous solution. The maximum adsorption capacity of the composite was 689.0 mg/g, which was achieved at pH 6. Nassar et al. [126] reported a maximum adsorption capacity of Fe₃O₄ nanoparticles for Pb (II) ions of 36.0 mg/g, which is much higher than the adsorption capacities of common adsorbents (Table 6). Beneficial adsorption characteristics have been

found for nano-oxide particles modified with Mn. For example, Warner et al. [127] used nano-oxide particles with and without Mn doping to adsorb heavy metal ions, and found that Mn doping strongly improved the affinities and capacities of the particles for the heavy metals Ag, As, Cd, Co, Hg, Ni, Ti, and Zn. Iron-oxide-based nanomaterials have high heavy metal ion adsorption capacities and adsorption rates, are simple to use and regenerate, and can be used instead of poorly efficient adsorbents.

Table 5. Adsorption capacities of modified polymers and other adsorbents for metal ions.

| Adsorbents | Metal Ions | Sorption Capacity (mmol/g) | Conditions | Reference |
|---|-------------------------------|----------------------------|---------------------------------|-----------|
| HCNSCR | Pb (II), Cd (II), and Zn (II) | 1.2, 1, and 0.9 | pH = 5.5, 6.0, and 6.3 25 °C | [115] |
| PAA-B/Z | Pb (II) | 0.16 | pH = 4.5 25 °C | [116] |
| Fe ₂ O ₃ –ceramisite (FOC) | Pb (II) and Zn (II) | 0.08 and 0.11 | pH = 5 25 °C | [117] |
| Olive stone activated carbon (COSAC) | Cd (II) and Pb (II) | 0.53 and 0.54 | pH = 5 30 °C | [118] |
| Amidoxime-modified poly (acrylonitrile-co-acrylic acid) | Cd (II) and Pb (II) | 0.18 and 0.6 | pH = 9 25 °C | [119] |
| Novel chelating sponge (PVA-M-H) | Ni (II) and Cd (II) | 1.114 and 1.117 | pH = 5.5 30 °C | [120] |
| Synthetic amberlite IR-120 | Ni (II), Cu (II), and Cd (II) | 0.819, 0.344, and 0.899 | pH = 9 25 °C | [121] |

HCNSCR, hyper-cross-linked nanoscale chelating resin; PAA-B/Z, polyacrylamide–bentonite/zeolite.

Table 6. Maximum Pb (II) adsorption capacities of various adsorbents.

| Adsorbing Material | Maximum Adsorption (mg/g) | Reference |
|--------------------------------|---------------------------|-----------|
| Nano oxide particle | 36.0 | [126] |
| Humic acid | 22.7 | [128] |
| Goethite | 11.04 | [128] |
| Montmorillonite | 33 | [129] |
| Al ₂ O ₃ | 17.5 | [130] |
| Diatomite | 24 | [131] |
| Activated carbon | 21.5 | [132] |

3.2. Treatment of Residual Organic Reagents

Xanthate is the most common collector when treating sulfide and oxidized ores [133,134]. Methods for removing xanthate from mineral processing wastewater are summarized in this section. Xanthate can be removed from flotation wastewater using biological, chemical, and physical techniques (Table 7). Traditional physical treatments, such as physical precipitation and activated carbon adsorption, have some drawbacks, including high costs and poor reusability; therefore, these treatments are not widely used [135]. Common methods for degrading xanthates using oxidizing agents, such as chlorine or permanganate, can cause secondary contamination because harmful byproducts are created [136]. Using microorganisms to bioremediate wastewater often requires a long degradation time, and it is difficult to degrade pollutants at low concentrations using biological treatments [137]. The treatment methods mentioned above are “traditional”, however, advanced oxidation techniques that efficiently produce active substances and rapidly remove organic pollutants have been developed [138]. Novel oxidation techniques for degrading xanthate include Fenton oxidation and photocatalytic oxidation.

Table 7. Traditional treatments and advanced oxidation treatments for removing xanthate from wastewater.

| | Progress | Characteristic |
|--|--|---|
| Traditional treatment technologies | Physical and chemical precipitation Activated carbon adsorption | High cost, poor reusability, and causes secondary contamination |
| Advanced oxidation technologies (AOTs) | Fenton oxidation Photocatalytic oxidation | High chemical activity and decontamination efficiency |

3.2.1. Photocatalytic Oxidation

Photocatalysis is one of the best methods for degrading harmful organic pollutants in wastewater because it is environmentally benign, sustainable, and cheap [139]. Titanium dioxide (TiO_2) is a photocatalytic material that has attracted much attention in recent years, and has often been found to be the optimal semiconductor photocatalyst [140,141]. However, TiO_2 has some disadvantages when used as a photocatalyst [142,143], including powder-like TiO_2 having a large bandgap (3.2 eV for anatase), photogenerated electron–hole pairs (e^-/h^+) readily and rapidly recombining, agglomeration occurring readily, and separation and recycling procedures being difficult; therefore, TiO_2 is not suitable for treating contaminated water [144].

The unsuitability of TiO_2 for use as a photocatalyst for treating wastewater can be solved to an extent by loading TiO_2 nanoparticles (TNPs) onto a supporting surface [145]. TNPs aggregate on the supporting material surface through various bonding methods, and the surface of the supporting material can act as an electron sink. The photocatalytic activity is markedly better in this composite material than in TiO_2 because less electron/hole recombination in the TiO_2 photocatalyst occurs. Some problems using TiO_2 to achieve photocatalysis have been solved using TiO_2 composites with silver orthophosphate (Ag_3PO_4) [146], BiOCl [139], clinoptilolite [145], and Nb_2O_5 [147]. As shown in Table 8, the bandgaps were found to be narrower for composite photocatalytic materials than for TiO_2 , resulting in the response in the visible spectrum to be stronger for composite photocatalytic materials than for TiO_2 .

Table 8. Bandgap widths for synthesized composite photocatalytic materials and TiO_2 .

| Material | Bandgap (eV) | Reference |
|---|--------------|-----------|
| TiO_2 | 3.09 | [145] |
| $\text{TiO}_2/\text{Clinoptilolite}$ | 2.88 | [145] |
| $\text{BiOCl}/\text{TiO}_2/\text{Clinoptilolite}$ | 2.56 | [139] |
| $\text{TiO}_2/\text{Nb}_2\text{O}_5$ | 2.59 | [147] |
| $\text{Ag}_3\text{PO}_4/\text{TiO}_2$ | 2.05 | [146] |

Zhou et al. [139] synthesized novel ternary heterogeneous $\text{BiOCl}/\text{TiO}_2/\text{clinoptilolite}$ (BTC) photocatalysts using a hydrothermal method combined with a water bath precipitation method using clinoptilolite as the supporting material. BiOCl is a ternary layered oxide with an internal structure that provides adequate space to facilitate the separation of the photogenerated e^-/h^+ pairs in the TNPs. Morphological analysis indicated that the clinoptilolite improved TNP dispersion on the composite surfaces. N_2 adsorption/desorption analysis indicated that there were many micropores in the BTC, which would provide it with a high adsorption capacity and ability to degrade xanthate. In degradation experiments, BTC was found to exhibit degradation rates for sodium ethyl xanthate, sodium butyl xanthate, and sodium isoamyl xanthate of 84.5%, 96.7%, and 99.2%, respectively. These data indicate that BTC performs well as a photocatalyst.

3.2.2. Fenton Oxidation

Fenton oxidation produces strongly oxidizing hydroxyl radicals ($\cdot\text{OH}$) that can effectively degrade otherwise recalcitrant organic pollutants [148–150]. Fenton oxidation is

a promising water treatment technique because the reagents are cheap and the method is simple and effective [151,152]. However, the Fenton process has some drawbacks that prevent it being used widely in industrial-scale wastewater treatment plants [153]. Improving wastewater treatment methods using the Fenton oxidation process is a current focus of research, and remarkable progress has been made using improved Fenton oxidation processes to remove xanthate residues from wastewater.

Improved versions of the traditional Fenton oxidation process include ultrasonication–Fenton oxidation [154], photocatalysis–Fenton oxidation [155], and electrocatalysis–Fenton oxidation [156]. Ai et al. [157] investigated xanthate degradation using a combination of ultrasonication and Fenton oxidation, and a greater removal efficiency was found using the combined method than using Fenton oxidation alone. At pH 3, a H_2O_2 concentration of 24 mg/L, and a Fe^{2+} concentration of 18 mg/L, 97.6% of the xanthate present was removed from real mineral processing wastewater, and the xanthate concentration in the treated wastewater met the relevant effluent discharge standard. Xanthate degradation in the ultrasonication–Fenton oxidation method [158–161] involves two processes. Ultrasonication causes the Fenton reagent to form more hydroxyl radicals ($\cdot\text{OH}$) in the water than would otherwise be produced, and the high temperatures and pressures generated in the cavitation bubbles are conducive to the Fenton reaction. The ultrasonic waves also increase the degree of liquid mass transfer that occurs, so the reacting species come into more contact with each other, which increases the reaction efficiency. Garcia et al. [162] assessed ethyl xanthate removal, degradation, and mineralization in a simulated solar Fenton advanced oxidation process, and a kinetics study indicated that the process performed well (~99% of xanthate anions were removed). Electrocatalysis–Fenton oxidation and photocatalysis–Fenton oxidation are generally used as combined processes. Yang et al. [163] found that ethyl xanthate was effectively degraded using bismuth ferrites based on activated bentonite (A-BiFe/Bent in Table 9) as particle electrodes in a three-dimensional electro-Fenton system under visible light. At Na_2SO_4 concentration of 0.10 mol/L, a concentration of bismuth ferrites based on activated bentonite of 1.0 g/L, an applied voltage of 10 V, an aeration intensity of 3.5 L/min, and at natural pH, the ethyl xanthate degradation efficiency and COD_{Cr} removal efficiency were 97.85% and 93.50%, respectively. These advanced oxidation processes can effectively remove xanthate from wastewater, often exhibiting removal efficiencies >95% (Table 9). However, homogeneous photocatalysis–Fenton oxidation has some clear disadvantages, including the aqueous solution having a low pH, and it being difficult to separate and reuse the iron ions in the $\text{Fe}^{2+}/\text{H}_2\text{O}_2/\text{UV}$ system. The latter will cause secondary pollution, which will increase the treatment cost; furthermore, the production of iron hydroxide sludge will cause other environmental problems [164–167]. Research into heterogeneous Fenton processes has therefore been performed. Composite heterogeneous catalysts, such as a bentonite-supported Fe (II)/phosphotungstic acid composite [168], acidified/calcined red mud [169], and modified fly ash [170], can overcome most of the problems associated with homogeneous Fenton processes and offer great potential for industrial applications.

Table 9. Xanthate degradation efficiencies achieved using various advanced oxidation processes.

| Process | Conditions | Removal Rate of Xanthate (%) | Reference |
|---------------------------------|---|------------------------------|-----------|
| Ultrasonic–Fenton oxidation | $c(\text{Fe}^{2+}) = 18 \text{ mg/L}$ $c(\text{H}_2\text{O}_2) = 24 \text{ mg/L}$ 40 kHz (Ultrasonic frequency) pH = 3 | 97.6 | [157] |
| Photocatalysis–Fenton oxidation | $[\text{Fe}^{2+}]: [\text{H}_2\text{O}_2] = 1:40$ (Molar ratio) pH = 9 30mW/cm ² (Irradiance) | 99.1 | [162] |

Table 9. Cont.

| Process | Conditions | Removal Rate of Xanthate (%) | Reference |
|-----------------------------------|---|------------------------------|-----------|
| Electrocatalysis–Fenton oxidation | $c(\text{Na}_2\text{SO}_4) = 0.10 \text{ mol/L}$ $c(\text{A-BiFe/Bent}) = 1 \text{ g/L}$ $U = 10 \text{ V}$ Aeration intensity 3.5 L/min $\text{pH} = 6.82$ | 97.85 | [163] |

4. Recycling and Utilization of Wastewater from Non-Ferrous Metal Mineral Processing

Mineral processing, particularly for non-ferrous metal production, consumes large amounts of freshwater resources. Many mineral processing plants are situated in remote mining areas to minimize transportation costs and limit the effects of the plants on humans; however, some such areas have inadequate freshwater supplies. It is therefore important to recycle the water using mineral processing plants and to develop efficient wastewater treatment processes, liquid–solid separation processes, and dehydration steps [171]. The effective recycling of flotation wastewater is key to recycling mineral processing wastewater.

4.1. Effects of Recycling Wastewater on Flotation Processes

Flotation wastewater has different qualities to freshwater; thus, using recycled water in a flotation process usually negatively affects mineral recovery and the concentrate quality [172]. The accumulation of dissolved inorganic and organic compounds in the water used in the flotation process can alter the chemical properties of the system. When recycling flotation wastewater, the accumulation of reagents and heavy metal ions in the wastewater can cause the flotation production index to weaken. The main factors affecting the recycling of flotation wastewater for further flotation processes include the presence of ions that cannot be removed, flotation reagent residues, and suspended solids. Cations and anions on the mineral surfaces, and calcium or magnesium ions in hard water, can affect the flotation process. When flotation wastewater is reused, reagent residues can be both beneficial and detrimental to the flotation process. The benefit is that some collector will remain in the flotation wastewater, so less fresh collector will need to be added when the wastewater is reused. The adverse effects of using recycling water are shown in Table 10.

Table 10. Adverse effects of using recycling water on flotation.

| Factors | Potential Effects |
|-------------------|---|
| Inevitable ions | <ol style="list-style-type: none"> 1. Consumption of flotation reagents. 2. Activation of gangue mineral. 3. Depression of the target mineral. |
| Residual reagents | <ol style="list-style-type: none"> 1. May have a depressive effect on the purpose mineral. 2. May activate the gangue mineral, making it difficult to separate the target mineral from the gangue mineral. 3. Could interact with inevitable ions to form complex, colloidal substances, etc., reducing the efficiency of flotation. |
| Suspended solids | <ol style="list-style-type: none"> 1. The surface of mineral particles could be covered by suspended solids, which affects the adsorption of reagents on the mineral surface. 2. The colloidal group generated by suspended solids will increase the pulp viscosity. |

4.2. Processes Involved in Recycling Flotation Wastewater

Wastewater recycling in the flotation process can be divided into two categories, known as external and internal recycling [172–175]. External recycling is where the total amount of wastewater is simply settled and used in different parts of the flotation process.

Internal recycling is where the water recovered from different parts of the process is returned to the corresponding loop.

4.2.1. External Recycling

The external recycling process (Figure 3) is mainly used for the flotation concentrate and tailing pond overflow water, which are allowed to settle naturally and then directly reused in the flotation process. Alternatively, depending on the reagent residue and heavy metal ion concentrations, the total amount of wastewater may be mixed with some new water before being used in the flotation process. This technique has various advantages, being relatively simple, cheap, and convenient, and is widely used in industrial plants. However, external recycling has some disadvantages. Mixing wastewater from different processes means the wastewater is usually of a complex composition. The reagent residue and heavy metal ion concentrations in the water increase as the number of cycles increase. Various chemical reactions occur between the anionic reagent residues and metal cations in the wastewater, causing the wastewater composition to become more complex. This may ultimately adversely affect the flotation index.

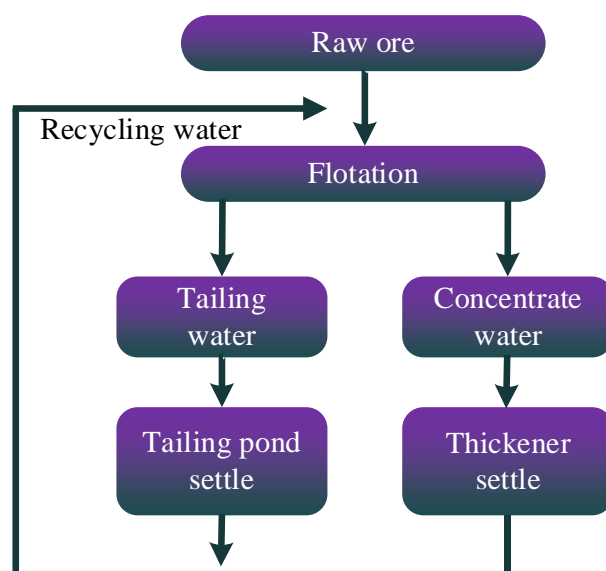


Figure 3. Schematic diagram of external recycling process of flotation wastewater.

4.2.2. Internal Recycling Process

The internal recycling process (Figure 4) involves selecting when to use recycled mineral processing wastewater according to the quality of the wastewater. The most common internal recycling process is described here. In the polymetallic flotation process, wastewater derived from the processing of a single metal concentrate is filtered and passed into a concentrating basin, in which purification treatments targeted at specific impurities are performed. The wastewater is then reused in the previous stage of the flotation process. This internal recycling process has four advantages and maintains a stable flotation index. These advantages are: (i) a smaller volume of wastewater needs to be treated compared to when wastewater is not recycled, (ii) few heavy metal ions and flotation reagents need to be removed, which greatly decreases the difficulty and cost of treating the wastewater, (iii) reagent residues in the wastewater are effectively utilized, which decreases the required reagent dose, (iv) the flotation process is cheaper compared to when wastewater is not recycled. However, more multiple return water cycles are required, and the process is more complex and difficult to manage when internal recycling is performed than when direct recycling of whole wastewater is performed.

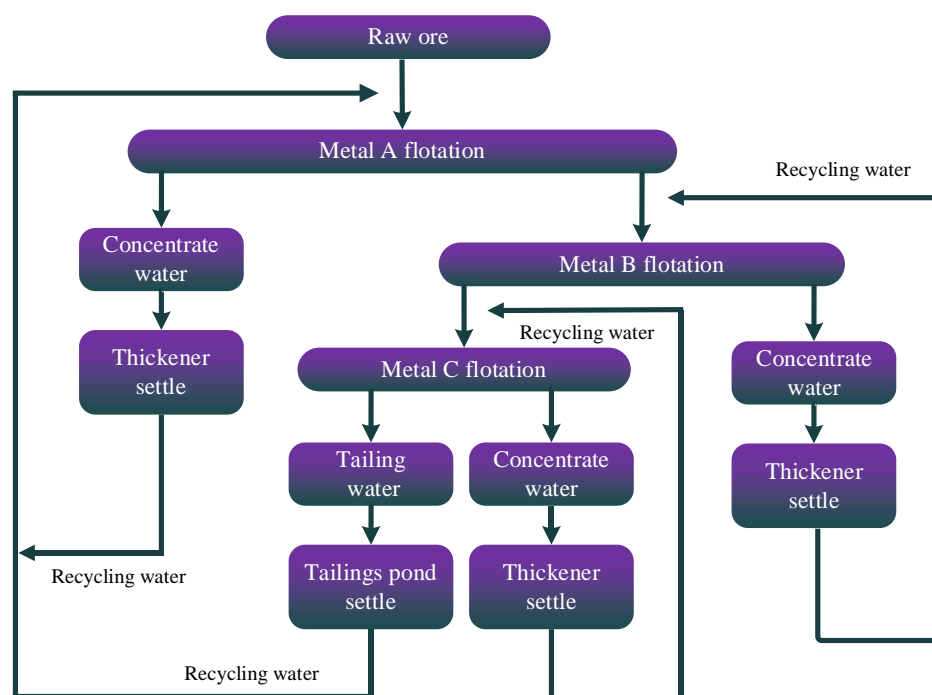


Figure 4. Internal recycling process of flotation wastewater. Metals A, B, and C represent different valuable metals in polymetallic mineral processing.

5. Conclusions

Heavy metals (e.g., copper, lead, and zinc) and xanthate are the main pollutants in non-ferrous metal mineral processing wastewater; therefore, it is important to remove these pollutants from wastewater before the wastewater is reused or released. Removing these pollutants can allow the effects of using recycled wastewater on mineral separation to be controlled, and can improve the wastewater utilization rate and decrease the pollution of the environment surrounding a mineral processing plant. Few practical studies of mineral processing wastewater treatments have been performed. The methods previously used to treat wastewater containing heavy metals and organic chemicals in various industries and laboratories are summarized above.

Chemical precipitation and adsorption methods are generally used to remove heavy metal ions from wastewater. Chemical precipitation is suitable for removing Cr, Cu, Hg, Ni, Zn, and other heavy metals from wastewater. Hydroxide precipitation can be used to economically and effectively treat wastewater containing a small number of heavy metals at high concentrations. Sulfide precipitation is more easily achieved than hydroxide precipitation because metal sulfides are more stable than metal hydroxides in sediment. Alternatively, adsorption is simpler to perform and cheaper than precipitation. Many high-performance polymers and modified nanomaterials have been developed that can be used to adsorb heavy metal ions from mineral processing wastewater.

The efficient degradation of organic reagents (e.g., xanthate) using advanced oxidation techniques has been achieved in the laboratory; thus, advanced oxidation techniques would be worth considering for treating non-ferrous metal mineral processing wastewater. The cost of an ultrasonic device needs to be considered before deciding to use the ultrasonic oxidation process, and electric consumption needs to be considered before using an oxidation process. Photocatalytic oxidation will be the most cost-effective treatment because sunlight is free. The only drawback of photocatalytic oxidation is that variations in light intensity will cause a variable xanthate degradation rate. Few treatments for removing fine suspended solids have been developed, possibly because fine suspended solids have little environmental impact and due to the long time period required for the natural settlement of fine suspended solids. Few studies of comprehensive treatment techniques for heavy

metal ions and organic reagents have been published. Developing such methods will be key to achieve efficient recycling of wastewater produced during the beneficiation process. Research into the comprehensive treatments of various pollutants in wastewater should be performed.

Recycling flotation wastewater is an effective way of preserving water resources and achieving clean production processes. Most mineral processing wastewater is produced during the flotation process. Flotation wastewater can be recycled using external or internal recycling processes. Recycling flotation wastewater has the advantages of decreasing production costs and environmental impacts. Recycling flotation wastewater can decrease the consumption of water and the quantities of reagents required for the flotation process, which will decrease production costs. Recycling flotation wastewater can also minimize the amount of wastewater discharged, and therefore decrease the impacts of mineral processing on the environment. Overall, recycling flotation wastewater is an important way of decreasing production costs and environmental impacts, and should be a top priority to allow the sustainable development of mining enterprises.

Author Contributions: S.M.: Data curation, Formal analysis, Investigation, Methodology, Software, Visualization, Writing—original draft, Writing—review & editing. S.W.: Investigation, Methodology, Project administration, Resources, Supervision, Validation, Writing—review & editing. G.H.: Formal analysis, Investigation, Methodology, Visualization, Writing—review & editing. X.W.: Investigation, Methodology, Visualization, Writing—review & editing. Q.F.: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Validation, Writing—review & editing. All authors have read and agreed to the published version of the manuscript.

Funding: This work was financially supported by Ten Thousand Talent Plans for Young Top-notch Talents of Yunnan Province (No. YNWR-QNBJ-2018-051).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

- Owodunni, A.A.; Suzylawati, I. Revolutionary technique for sustainable plant-based green coagulants in industrial wastewater treatment—A review. *Water Process Eng.* **2021**, *42*, 102096. [\[CrossRef\]](#)
- Wang, C.T.; Wang, G.; Feng, Z. Comprehensive utilization of the water resources in small watershed. *Procedia Environ. Sci.* **2011**, *10*, 1509–1512. [\[CrossRef\]](#)
- Gleeson, T.; Wada, Y.; Bierkens, M.F.P. Water balance of global aquifers revealed by groundwater footprint. *Nature* **2012**, *488*, 197–200. [\[CrossRef\]](#) [\[PubMed\]](#)
- Zhang, G.; Hoekstra, A.Y.; Mathews, R.E. Water Footprint Assessment (WFA) for better water governance and sustainable development, editorial. *Water Resour. Ind.* **2013**, *1*, 1–6. [\[CrossRef\]](#)
- Malek, A.; Rao, G.R.; Thomas, T. Waste-to-wealth approach in water economy: The case of beneficiation of mercury-contaminated water in hydrogen production. *Int. J. Hydrog. Energy* **2021**, *46*, 26677–26692. [\[CrossRef\]](#)
- Dubey, A.K.; Sahu, O. Review on natural methods for waste water treatment. *J. Urban Environ. Eng.* **2014**, *8*, 89–97.
- Mwaanga, P.; Silondwa, M.; Kasali, G. Preliminary review of mine air pollution in Zambia. *Heliyon* **2019**, *5*, e02485. [\[CrossRef\]](#)
- Ran, H.; Guo, Z.; Yi, L. Pollution characteristics and source identification of soil metal (loid) s at an abandoned arsenic-containing mine, China. *J. Hazard. Mater.* **2021**, *413*, 125382. [\[CrossRef\]](#)
- Bhuiyan, M.A.H.; Parvez, L.; Islam, M.A. Heavy metal pollution of coal mine-affected agricultural soils in the northern part of Bangladesh. *J. Hazard. Mater.* **2010**, *173*, 384–392. [\[CrossRef\]](#)
- Antunes, I.; Gomes, M.E.P.; Neiva, A.M.R. Potential risk assessment in stream sediments, soils and waters after remediation in an abandoned W > Sn mine (NE Portugal). *Ecotoxicol. Environ. Saf.* **2016**, *133*, 135–145. [\[CrossRef\]](#)
- Xin, R.R.; Banda, J.F.; Hao, C.B. Contrasting seasonal variations of geochemistry and microbial community in two adjacent acid mine drainage lakes in Anhui Province, China. *Environ. Pollut.* **2021**, *268*, 115826. [\[CrossRef\]](#) [\[PubMed\]](#)
- Stewart, B.D.; Jenkins, S.R.; Boig, C. Metal pollution as a potential threat to shell strength and survival in marine bivalves. *Sci. Total Environ.* **2021**, *755*, 143019. [\[CrossRef\]](#) [\[PubMed\]](#)

13. Pelletier, N.; Chételat, J.; Cousens, B. Lead contamination from gold mining in Yellowknife Bay (Northwest Territories), reconstructed using stable lead isotopes. *Environ. Pollut.* **2020**, *259*, 113888. [\[CrossRef\]](#) [\[PubMed\]](#)
14. Luís, A.T.; Teixeira, P.; Almeida, S.F.P. Environmental impact of mining activities in the Lousal area (Portugal): Chemical and diatom characterization of metal-contaminated stream sediments and surface water of Corona stream. *Sci. Total Environ.* **2011**, *409*, 4312–4325. [\[CrossRef\]](#) [\[PubMed\]](#)
15. Park, J.H.; Oh, C.; Han, Y.S. Optimizing the addition of flocculants for recycling mineral-processing wastewater. *Geosyst. Eng.* **2016**, *19*, 83–88. [\[CrossRef\]](#)
16. Benavente, M.; Moreno, L.; Martinez, J. Sorption of heavy metals from gold mining wastewater using chitosan. *J. Taiwan Inst. Chem. Eng.* **2011**, *42*, 976–988. [\[CrossRef\]](#)
17. Meriç, S.; Selçuk, H.; Belgiorno, V. Acute toxicity removal in textile finishing wastewater by Fenton's oxidation, ozone and coagulation–flocculation processes. *Water Res.* **2005**, *39*, 1147–1153. [\[CrossRef\]](#)
18. Hu, X.F.; Jiang, Y.; Shu, Y. Effects of mining wastewater discharges on heavy metal pollution and soil enzyme activity of the paddy fields. *J. Geochem. Explor.* **2014**, *169*, 139–150. [\[CrossRef\]](#)
19. Han, G.; Wen, S.M.; Wang, H.; Feng, Q.C. Surface sulfidization mechanism of cuprite and its response to xanthate adsorption and flotation performance. *Miner. Eng.* **2021**, *169*, 106982. [\[CrossRef\]](#)
20. Rani, C.N.; Karthikeyan, S.; Doss, S.P.A. Photocatalytic ultrafiltration membrane reactors in water and wastewater treatment-A review. *Chem. Eng. Process.-Process Intensif.* **2021**, *165*, 108445. [\[CrossRef\]](#)
21. Xu, Y.; Schwartz, F.W. Lead immobilization by hydroxyapatite in aqueous solutions. *J. Contam. Hydrol.* **1994**, *15*, 187–206. [\[CrossRef\]](#)
22. Yang, M.; Lin, L.; Wang, B. A facile yet versatile method for adsorption and relayed fluorescent detection of heavy metal ions. *J. Environ. Chem. Eng.* **2021**, *9*, 105737. [\[CrossRef\]](#)
23. Zhang, C.J.; Hu, M.; Ke, Q.F.; Guo, C.X.; Guo, Y.J.; Guo, Y.P. Nacre-inspired hydroxyapatite/chitosan layered composites effectively remove lead ions in continuous-flow wastewater. *J. Hazard. Mater.* **2020**, *386*, 121999. [\[CrossRef\]](#) [\[PubMed\]](#)
24. Li, Z.; Wang, Z.; Wang, C. Preparation of magnetic resin microspheres MP (MMA-DVB-GMA) and the adsorption property to heavy metal ions. *Appl. Surf. Sci.* **2019**, *496*, 143708. [\[CrossRef\]](#)
25. Tzu, T.W.; Tsuritani, T.; Sato, K. Sorption of Pb (II), Cd (II), and Ni (II) toxic metal ions by alginate-bentonite. *J. Environ. Prot.* **2013**, *4*, 51–55. [\[CrossRef\]](#)
26. Najam, R.; Andrabi, S.M.A. Removal of Cu (II), Zn (II) and Cd (II) ions from aqueous solutions by adsorption on walnut shell-Equilibrium and thermodynamic studies: Treatment of effluents from electroplating industry. *Desalin. Water Treat.* **2016**, *57*, 27363–27373. [\[CrossRef\]](#)
27. Alkherraz, A.M.; Ali, A.K.; Elsherif, K.M. Removal of Pb (II), Zn (II), Cu (II) and Cd (II) from aqueous solutions by adsorption onto olive branches activated carbon: Equilibrium and thermodynamic studies. *Chem. Int.* **2020**, *6*, 11–20.
28. Joseph, I.V.; Tosheva, L.; Doyle, A.M. Simultaneous removal of Cd (II), Co (II), Cu (II), Pb (II), and Zn (II) ions from aqueous solutions via adsorption on FAU-type zeolites prepared from coal fly ash. *J. Environ. Chem. Eng.* **2020**, *8*, 103895. [\[CrossRef\]](#)
29. Jagung, P.T. Removal of Zn (II), Cd (II) and Mn (II) from aqueous solutions by adsorption on maize stalks. *Malays. J. Anal. Sci.* **2011**, *15*, 8–21.
30. Guo, S.; Wu, K.; Gao, Y. Efficient removal of Zn (II), Pb (II), and Cd (II) in waste water based on magnetic graphitic carbon nitride materials with enhanced adsorption capacity. *J. Chem. Eng. Data* **2018**, *63*, 3902–3912. [\[CrossRef\]](#)
31. Dabrowski, A.; Hubicki, Z.; Podkościelny, P. Selective removal of the heavy metal ions from waters and industrial wastewaters by ion-exchange method. *Chemosphere* **2004**, *56*, 91–106. [\[CrossRef\]](#)
32. Vaaramaa, K.; Lehto, J. Removal of metals and anions from drinking water by ion exchange. *Desalination* **2003**, *155*, 157–170. [\[CrossRef\]](#)
33. Wang, R.; Guan, S.; Sato, A. Nanofibrous microfiltration membranes capable of removing bacteria, viruses and heavy metal ions. *J. Membr. Sci.* **2013**, *446*, 376–382. [\[CrossRef\]](#)
34. Zhong, Y.J.; You, S.J.; Wang, X.H. Synthesis of carbonaceous nanowire membrane for removing heavy metal ions and highwater flux. *Chem. Eng. J.* **2013**, *226*, 217–226. [\[CrossRef\]](#)
35. Hezarjaribi, M.; Bakeri, G.; Sillanpää, M. Novel adsorptive PVC nanofibrous/thiol-functionalized TNT composite UF membranes for effective dynamic removal of heavy metal ions. *J. Environ. Manag.* **2021**, *284*, 111996. [\[CrossRef\]](#)
36. Mu, J.; Zhou, H.; Chen, Y. Revealing a novel natural bioflocculant resource from *Ruditapes philippinarum*: Effective polysaccharides and synergistic flocculation. *Carbohydr. Polym.* **2018**, *186*, 17–24. [\[CrossRef\]](#)
37. Xiao, X.; Sun, Y.; Liu, J. Flocculation of heavy metal by functionalized starch-based bioflocculants: Characterization and process evaluation. *Sep. Purif. Technol.* **2021**, *267*, 118628. [\[CrossRef\]](#)
38. Yang, K.; Wang, G.; Chen, X. Treatment of wastewater containing Cu²⁺ using a novel macromolecular heavy metal chelating flocculant xanthated chitosan. *Colloids Surf. A Physicochem. Eng. Asp.* **2018**, *558*, 384–391. [\[CrossRef\]](#)
39. Nguyen, M.K.; Pham, T.T.; Pham, H.G. Fenton/ozone-based oxidation and coagulation processes for removing metals (Cu, Ni)-EDTA from plating wastewater. *J. Water Process Eng.* **2021**, *39*, 101836. [\[CrossRef\]](#)
40. Wang, Y.; Pan, T.; Yu, Y. A novel peroxymonosulfate (PMS)-enhanced iron coagulation process for simultaneous removal of trace organic pollutants in water. *Water Res.* **2020**, *185*, 116136. [\[CrossRef\]](#)

41. Ali, I.; Asim, M.; Khan, T.A. Lowcost adsorbents for the removal of organic pollutants from wastewater. *J. Environ. Manag.* **2012**, *113*, 170–183. [\[CrossRef\]](#)
42. Feng, Y.; Yang, S.; Xia, L. In-situ ion exchange electrocatalysis biological coupling (i-IEEBC) for simultaneously enhanced degradation of organic pollutants and heavy metals in electroplating wastewater. *J. Hazard. Mater.* **2019**, *364*, 562–570. [\[CrossRef\]](#) [\[PubMed\]](#)
43. Moreira, F.C.; Boaventura, R.A.R.; Brillas, E. Electrochemical advanced oxidation processes: A review on their application to synthetic and real wastewaters. *Appl. Catal. B Environ.* **2017**, *202*, 217–261. [\[CrossRef\]](#)
44. Tony, M.A.; Mansour, S.A.; Tayeb, A.M. Use of a fenton-like process based on nano-haematite to treat synthetic wastewater contaminated by phenol: Process investigation and statistical optimization. *Arab. J. Sci. Eng.* **2018**, *43*, 2227–2235. [\[CrossRef\]](#)
45. Martínez-Huitle, C.A.; Panizza, M. Electrochemical oxidation of organic pollutants for wastewater treatment. *Curr. Opin. Electrochem.* **2018**, *11*, 62–71. [\[CrossRef\]](#)
46. Scialdone, O. Electrochemical oxidation of organic pollutants in water at metal oxide electrodes: A simple theoretical model including direct and indirect oxidation processes at the anodic surface. *Electrochim. Acta* **2009**, *54*, 6140–6147. [\[CrossRef\]](#)
47. Comninellis, C. Electrochemical Oxidation of Organic Pollutants for Wastewater Treatment. *Stud. Environ. Sci.* **1994**, *59*, 77–102.
48. He, Y.; Lin, H.; Guo, Z. Recent developments and advances in boron-doped diamond electrodes for electrochemical oxidation of organic pollutants. *Sep. Purif. Technol.* **2019**, *212*, 802–821. [\[CrossRef\]](#)
49. Daghrir, R.; Drogui, P.; Robert, D. Photoelectrocatalytic technologies for environmental applications. *J. Photochem. Photobiol. A Chem.* **2012**, *238*, 41–52. [\[CrossRef\]](#)
50. Kim, G.; Iggunu, E.T.; Chen, G.Z. A sunlight assisted dual purpose photoelectrochemical cell for low voltage removal of heavy metals and organic pollutants in wastewater. *Chem. Eng. J.* **2014**, *244*, 411–421. [\[CrossRef\]](#)
51. Liu, C.; Ding, Y.; Wu, W. A simple and effective strategy to fast remove chromium (VI) and organic pollutant in photoelectrocatalytic process at low voltage. *Chem. Eng. J.* **2016**, *306*, 22–30. [\[CrossRef\]](#)
52. Mehta, S.K.; Gaur, J.P. Use of algae for removing heavy metal ions from wastewater: Progress and prospects. *Crit. Rev. Biotechnol.* **2005**, *25*, 113–152. [\[CrossRef\]](#) [\[PubMed\]](#)
53. Ngah, W.S.W.; Hanafiah, M.A.K.M. Removal of heavy metal ions from wastewater by chemically modified plant wastes as adsorbents: A review. *Bioresour. Technol.* **2008**, *99*, 3935–3948. [\[CrossRef\]](#) [\[PubMed\]](#)
54. Fu, F.; Wang, Q. Removal of heavy metal ions from wastewaters: A review. *J. Environ. Manag.* **2011**, *92*, 407–418. [\[CrossRef\]](#)
55. Cabral Pinto, M.; Silva, M.; Silva, E.A. The cancer and non-cancer risk of Santiago Island (Cape Verde) population due to potential toxic elements exposure from soils. *Geosciences* **2017**, *7*, 78. [\[CrossRef\]](#)
56. Kumar, A.; Cabral-Pinto, M.; Kumar, M. Estimation of risk to the eco-environment and human health of using heavy metals in the Uttarakhand Himalaya, India. *Appl. Sci.* **2020**, *10*, 7078. [\[CrossRef\]](#)
57. Adriano, D.C.; Wenzel, W.W.; Vangronsveld, J. Role of assisted natural remediation in environmental cleanup. *Geoderma* **2004**, *122*, 121–142. [\[CrossRef\]](#)
58. Paithankar, J.G.; Saini, S.; Dwivedi, S. Heavy metal associated health hazards: An interplay of oxidative stress and signal transduction. *Chemosphere* **2021**, *262*, 128350. [\[CrossRef\]](#)
59. Qin, G.; Niu, Z.; Yu, J. Soil heavy metal pollution and food safety in China: Effects, sources and removing technology. *Chemosphere* **2020**, *267*, 129205. [\[CrossRef\]](#)
60. Corguinha, A.P.B.; Souza, G.A.; Gonçalves, V.C. Assessing arsenic, cadmium, and lead contents in major crops in Brazil for food safety purposes. *J. Food Compos. Anal.* **2015**, *37*, 143–150. [\[CrossRef\]](#)
61. Kumar, S.; Trivedi, P.K. Heavy metal stress signaling in plants. In *Plant Metal Interaction*; Parvaiz, A., Ed.; Elsevier: Amsterdam, The Netherlands, 2016; Chapter 25; pp. 585–603.
62. Tchounwou, P.B.; Yedjou, C.G.; Patlolla, A.K. Heavy metal toxicity and the environment. *Mol. Clin. Environ. Toxicol.* **2012**, *101*, 133–164.
63. Jaishankar, M.; Tseten, T.; Anbalagan, N. Toxicity, mechanism and health effects of some heavy metals. *Interdiscip. Toxicol.* **2014**, *7*, 60. [\[CrossRef\]](#)
64. Jarvis, A.P.; Younger, P.L. Broadening the scope of mine water environmental impact assessment: A UK perspective. *Environ. Impact Assess. Rev.* **2000**, *20*, 85–96. [\[CrossRef\]](#)
65. Lanocha-Arendarczyk, N.; Kosik-Bogacka, D.I.; Kalisinska, E. Influence of environmental factors and relationships between vanadium, chromium, and calcium in human bone. *BioMed Res. Int.* **2016**, *2016*, 8340425. [\[CrossRef\]](#) [\[PubMed\]](#)
66. Wang, X.; Liu, J.; Zhu, Y. Adsorption and depression mechanism of an eco-friendly depressant PCA onto chalcopyrite and pyrite for the efficiency flotation separation. *Colloids Surf. A Physicochem. Eng. Asp.* **2021**, *620*, 126574. [\[CrossRef\]](#)
67. Cañizares, P.; Lobato, J.; Paz, R. Advanced oxidation processes for the treatment of olive-oil mills wastewater. *Chemosphere* **2007**, *67*, 832–838. [\[CrossRef\]](#)
68. Yay, A.S.E.; Oral, H.V.; Onay, T.T. A study on olive oil mill wastewater management in Turkey: A questionnaire and experimental approach. *Resour. Conserv. Recycl.* **2012**, *60*, 64–71.
69. Amor, C.; Lucas, M.S.; Garcia, J. Combined treatment of olive mill wastewater by Fenton's reagent and anaerobic biological process. *J. Environ. Sci. Health Part A* **2015**, *50*, 161–168. [\[CrossRef\]](#)
70. Han, G.; Wen, S.M.; Wang, H.; Feng, Q.C. Enhanced sulfidization flotation of cuprite by surface modification with hydrogen peroxide. *Trans. Nonferrous Met. Soc. China* **2021**, *31*, 3564–3578. [\[CrossRef\]](#)

71. Oliveira, J.G.G. Desenvolvimento de Uma Rota de Processo de Dessulfurização de Rejeitos de Um Minério Aurífero Sulfetado. Master's Thesis, Federal University of Minas, Minas Gerais, Brazil, 2011.
72. Hu, J.S.; Zhong, L.S.; Song, W.G. Synthesis of hierarchically structured metal oxides and their application in heavy metal ion removal. *Adv. Mater.* **2008**, *20*, 2977–2982. [\[CrossRef\]](#)
73. Liang, H.; Song, B.; Peng, P. Preparation of three-dimensional honeycomb carbon materials and their adsorption of Cr (VI). *Chem. Eng. J.* **2019**, *367*, 9–16. [\[CrossRef\]](#)
74. Ge, Y.; Li, Z. Application of lignin and its derivatives in adsorption of heavy metal ions in water: A review. *ACS Sustain. Chem. Eng.* **2018**, *6*, 7181–7192. [\[CrossRef\]](#)
75. Wu, R. Removal of heavy metal ions from industrial wastewater based on chemical precipitation method. *Ekoloji* **2019**, *28*, 2443–2452.
76. Mirbagheri, S.A.; Hosseini, S.N. Pilot plant investigation on petrochemical wastewater treatment for the removal of copper and chromium with the objective of reuse. *Desalination* **2005**, *171*, 85–93. [\[CrossRef\]](#)
77. Giannopoulou, I.; Papias, D. Differential precipitation of copper and nickel from acidic polymetallic aqueous solutions. *Hydrometallurgy* **2008**, *90*, 137–146. [\[CrossRef\]](#)
78. Charentanyarak, L. Heavy metals removal by chemical coagulation and precipitation. *Water Sci. Technol.* **1999**, *39*, 135–138. [\[CrossRef\]](#)
79. Özverdi, A.; Erdem, M. Cu²⁺, Cd²⁺ and Pb²⁺ adsorption from aqueous solutions by pyrite and synthetic iron sulphide. *J. Hazard. Mater.* **2006**, *137*, 626–632. [\[CrossRef\]](#)
80. Ghirisan, A.L.; Drăgan, S.; Pop, A. Heavy metal removal and neutralization of acid mine waste water-kinetic study. *Can. J. Chem. Eng.* **2007**, *85*, 900–905. [\[CrossRef\]](#)
81. Ghosh, P.; Samanta, A.N.; Ray, S. Reduction of COD and removal of Zn²⁺ from rayon industry wastewater by combined electro-Fenton treatment and chemical precipitation. *Desalination* **2011**, *266*, 213–217. [\[CrossRef\]](#)
82. Chen, Q.; Luo, Z.; Hills, C. Precipitation of heavy metals from wastewater using simulated flue gas: Sequent additions of fly ash, lime and carbon dioxide. *Water Res.* **2009**, *43*, 2605–2614. [\[CrossRef\]](#)
83. Guo, Z.R.; Zhang, G.; Fang, J. Enhanced chromium recovery from tanning wastewater. *J. Clean. Prod.* **2006**, *14*, 75–79. [\[CrossRef\]](#)
84. Alvarez, M.T.; Crespo, C.; Mattiasson, B. Precipitation of Zn (II), Cu (II) and Pb (II) at bench-scale using biogenic hydrogen sulfide from the utilization of volatile fatty acids. *Chemosphere* **2007**, *66*, 1677–1683. [\[CrossRef\]](#) [\[PubMed\]](#)
85. Brown, J.R.; Bancroft, G.M.; Fyfe, W.S. Mercury removal from water by iron sulfide minerals. An electron spectroscopy for chemical analysis (ESCA) study. *Environ. Sci. Technol.* **1979**, *13*, 1142–1144. [\[CrossRef\]](#)
86. Cheremisinoff, P.N. Activated Carbon/Ion Exchange. In *Handbook of Water and Wastewater Treatment Technology*; Cheremisinoff, P.N., Ed.; Routledge: Boca Raton, FL, USA, 1995; Volume 1, Chapter 10; pp. 371–411.
87. Verbych, S.; Hilal, N.; Sorokin, G. Ion exchange extraction of heavy metal ions from wastewater. *Sep. Sci. Technol.* **2005**, *39*, 2031–2040. [\[CrossRef\]](#)
88. Motsi, T.; Rowson, N.A.; Simmons, M.J.H. Adsorption of heavy metals from acid mine drainage by natural zeolite. *Int. J. Miner. Process.* **2009**, *92*, 42–48. [\[CrossRef\]](#)
89. Kang, S.Y.; Lee, J.U.; Moon, S.H. Competitive adsorption characteristics of Co²⁺, Ni²⁺, and Cr³⁺ by IRN-77 cation exchange resin in synthesized wastewater. *Chemosphere* **2004**, *56*, 141–147. [\[CrossRef\]](#)
90. Cavaco, S.A.; Fernandes, S.; Quina, M.M. Removal of chromium from electroplating industry effluents by ion exchange resins. *J. Hazard. Mater.* **2007**, *144*, 634–638. [\[CrossRef\]](#)
91. Siddiqui, W.A.; Khan, S.A. Synthesis, characterization and ion-exchange properties of a new and novel 'organic-inorganic' hybrid cation-exchanger: Poly (methyl methacrylate) Zr (IV) phosphate. *Colloids Surf. A Physicochem. Eng. Asp.* **2007**, *295*, 193–199. [\[CrossRef\]](#)
92. Singare, P.U.; Lokhande, R.S. Studies on ion-isotopic exchange reactions using nuclear grade ion exchange resins. *Ionics* **2012**, *18*, 351–357. [\[CrossRef\]](#)
93. Inamuddin, K.S.A.; Siddiqui, W.A.; Khan, A.A. Synthesis, characterization and ion-exchange properties of a new and novel 'organic-inorganic' hybrid cation-exchanger: Nylon-6, 6, Zr (IV) phosphate. *Talanta* **2007**, *71*, 841–847. [\[CrossRef\]](#)
94. Naushad, M.; AlOthman, Z.A.; Sharma, G. Kinetics, isotherm and thermodynamic investigations for the adsorption of Co (II) ion onto crystal violet modified amberlite IR-120 resin. *Ionics* **2015**, *21*, 1453–1459. [\[CrossRef\]](#)
95. Khan, A.A.; Alam, M.M. Preparation, characterization and analytical applications of a new and novel electrically conducting fibrous type polymeric-inorganic composite material: Polypyrrole Th (IV) phosphate used as a cation-exchanger and Pb (II) ion-selective membrane electrode. *Mater. Res. Bull.* **2005**, *40*, 289–305. [\[CrossRef\]](#)
96. Varshney, K.; Agrawal, A.; Mojumdar, S. Pyridine based cerium (IV) phosphate hybrid fibrous ion exchanger: Synthesis, characterization and thermal behaviour. *J. Therm. Anal. Calorim.* **2007**, *90*, 731–734. [\[CrossRef\]](#)
97. Khan, A.A.; Alam, M.M.; Mohammad, F. Ion-exchange kinetics and electrical conductivity studies of polyaniline Sn (IV) tungstoarsenate; (SnO₂) (WO₃) (As₂O₅)₄ (-C₆H₅-NH-)₂ · nH₂O: A new semi-crystalline 'polymeric-inorganic' composite cation-exchange material. *Electrochim. Acta* **2003**, *48*, 2463–2472. [\[CrossRef\]](#)
98. Khan, A.A.; Alam, M.M. New and novel organic-inorganic type crystalline 'polypyrrole/polyantimonic acid' composite system: Preparation, characterization and analytical applications as a cation-exchange material and Hg (II) ion-selective membrane electrode. *Anal. Chim. Acta* **2004**, *504*, 253–264. [\[CrossRef\]](#)

99. Khan, A.A.; Alam, M.M. Synthesis, characterization and analytical applications of a new and novel 'organic-inorganic' composite material as a cation exchanger and Cd (II) ion-selective membrane electrode: Polyaniline Sn (IV) tungstoarsenate. *React. Funct. Polym.* **2003**, *55*, 277–290. [\[CrossRef\]](#)
100. Varshney, K.G.; Tayal, N.; Khan, A.A.; Niwas, S. Synthesis, characterization and analytical applications of lead (II) selective polyacrylonitrile thorium (IV) phosphate: A novel fibrous ion exchanger. *Colloids Surf. A Physicochem. Eng. Asp.* **2001**, *181*, 123–129. [\[CrossRef\]](#)
101. Gupta, A.P.; Agarwal, H.; Ikram, S. Studies on a new composites material polyanilinezirconium (IV) tungstophosphate-a thorium (IV) selective cation exchanger. *J. Indian Chem. Soc.* **2003**, *80*, 57–59.
102. Nabi, S.A.; Shahadat, M.; Bushra, R. Development of composite ion-exchange adsorbent for pollutants removal from environmental wastes. *Chem. Eng. J.* **2010**, *165*, 405–412. [\[CrossRef\]](#)
103. Nabi, S.A.; Shahadat, M.; Bushra, R. Heavy-metals separation from industrial effluent, natural water as well as from synthetic mixture using synthesized novel composite adsorbent. *Chem. Eng. J.* **2011**, *175*, 8–16. [\[CrossRef\]](#)
104. Nabi, S.A.; Naushad, M.; Bushra, R. Synthesis and characterization of a new organic-inorganic Pb²⁺ selective composite cation exchanger acrylonitrile stannic (IV) tungstate and its analytical applications. *Chem. Eng. J.* **2009**, *152*, 80–87. [\[CrossRef\]](#)
105. Nabi, S.A.; Raeissi, A.S.; Shahadat, M. Synthesis and characterization of novel cation exchange adsorbent for the treatment of real samples for metal ions. *Chem. Eng. J.* **2012**, *200*, 426–432. [\[CrossRef\]](#)
106. Zonoz, F.M.; Ahmadi, S.J.; Nosrati, S.A. Preparation and characterization of zirconium (IV) molybdo tungsto vanado silicate as a novel inorganic ion exchanger in sorption of radionuclides. *J. Hazard. Mater.* **2009**, *169*, 808–812. [\[CrossRef\]](#)
107. Khan, M.A.; Bushra, R.; Ahmad, A. Ion exchangers as adsorbents for removing metals from aquatic media. *Arch. Environ. Contam. Toxicol.* **2014**, *66*, 259–269. [\[CrossRef\]](#) [\[PubMed\]](#)
108. Wang, X.; Deng, W.; Xie, Y. Selective removal of mercury ions using a chitosan-poly (vinyl alcohol) hydrogel adsorbent with three-dimensional network structure. *Chem. Eng. J.* **2013**, *228*, 232–242. [\[CrossRef\]](#)
109. Godiya, C.B.; Cheng, X.; Li, D. Carboxymethyl cellulose/polyacrylamide composite hydrogel for cascaded treatment/reuse of heavy metal ions in wastewater. *J. Hazard. Mater.* **2019**, *364*, 28–38. [\[CrossRef\]](#) [\[PubMed\]](#)
110. Kadirvelu, K.; Thamaraiselvi, K.; Namasivayam, C. Removal of heavy metals from industrial wastewaters by adsorption onto activated carbon prepared from an agricultural solid waste. *Bioresour. Technol.* **2001**, *76*, 63–65. [\[CrossRef\]](#)
111. Pan, B.; Zhang, W. Development of polymeric and polymer-based hybrid adsorbents for pollutants removal from waters. *Chem. Eng. J.* **2009**, *151*, 19–29. [\[CrossRef\]](#)
112. Zhao, X.; Lv, L.; Pan, B. Polymer-supported nanocomposites for environmental application: A review. *Chem. Eng. J.* **2011**, *170*, 381–394. [\[CrossRef\]](#)
113. Mahmud, E.; Huq, O.; Yahya, R. The removal of heavy metal ions from wastewater/aqueous solution using polypyrrole-based adsorbents: A review. *RSC Adv.* **2016**, *6*, 14778–14791. [\[CrossRef\]](#)
114. Zhang, S.; Zeng, M.; Xu, W. Polyaniline nanorods dotted on graphene oxide nanosheets as a novel super adsorbent for Cr (VI). *Dalton Trans.* **2013**, *42*, 7854–7858. [\[CrossRef\]](#) [\[PubMed\]](#)
115. El, H.M.; Shaaban, A.F.; ElKhawaga, H.A. Effective removal of Pb (II), Cd (II) and Zn (II) from aqueous solution by a novel hyper cross-linked nanometer-sized chelating resin. *J. Environ. Chem. Eng.* **2020**, *8*, 103788.
116. Ulusoy, U.; Şimşek, S. Lead removal by polyacrylamide-bentonite and zeolite composites: Effect of phytic acid immobilization. *J. Hazard. Mater.* **2005**, *127*, 163–171. [\[CrossRef\]](#) [\[PubMed\]](#)
117. Yuan, L.; Liu, Y. Removal of Pb (II) and Zn (II) from aqueous solution by ceramisite prepared by sintering bentonite, iron powder and activated carbon. *Chem. Eng. J.* **2013**, *215*, 432–439. [\[CrossRef\]](#)
118. Bohli, T.; Villaescusa, I.; Ouederni, A. Comparative study of bivalent cationic metals adsorption Pb (II), Cd (II), Ni (II) and Cu (II) on olive stones chemically activated carbon. *J. Chem. Eng. Process Technol.* **2013**, *4*, 1–7. [\[CrossRef\]](#)
119. Cho, H.H.; Wepasnick, K.; Smith, B.A. Sorption of aqueous Zn (II) and Cd (II) by multiwall carbon nanotubes: The relative roles of oxygen-containing functional groups and graphenic carbon. *Langmuir* **2010**, *26*, 967–981. [\[CrossRef\]](#) [\[PubMed\]](#)
120. Cheng, C.; Wang, J.; Yang, X. Adsorption of Ni (II) and Cd (II) from water by novel chelating sponge and the effect of alkali-earth metal ions on the adsorption. *J. Hazard. Mater.* **2014**, *264*, 332–341. [\[CrossRef\]](#)
121. Demirbas, A.; Pehlivan, E.; Gode, F. Adsorption of Cu (II), Zn (II), Ni (II), Pb (II), and Cd (II) from aqueous solution on Amberlite IR-120 synthetic resin. *J. Colloid Interface Sci.* **2005**, *282*, 20–25. [\[CrossRef\]](#)
122. Dave, P.N.; Chopda, L.V. Application of iron oxide nanomaterials for the removal of heavy metals. *J. Nanotechnol.* **2014**, *2014*, 14. [\[CrossRef\]](#)
123. Agrawal, A.; Sahu, K.K. Kinetic and isotherm studies of cadmium adsorption on manganese nodule residue. *J. Hazard. Mater.* **2006**, *137*, 915–924. [\[CrossRef\]](#)
124. Xu, P.; Zeng, G.M.; Huang, D.L. Use of iron oxide nanomaterials in wastewater treatment: A review. *Sci. Total Environ.* **2012**, *424*, 1–10. [\[CrossRef\]](#)
125. Fang, R.; Lu, C.; Zhong, Y. Puffed rice carbon with coupled sulfur and metal iron for high-efficiency mercury removal in aqueous solution. *Environ. Sci. Technol.* **2020**, *54*, 2539–2547. [\[CrossRef\]](#)
126. Nassar, N.N. Rapid removal and recovery of Pb (II) from wastewater by magnetic nanoadsorbents. *J. Hazard. Mater.* **2010**, *184*, 538–546. [\[CrossRef\]](#) [\[PubMed\]](#)

127. Warner, C.L.; Chouyyok, W.; Mackie, K.E. Manganese doping of magnetic iron oxide nanoparticles: Tailoring surface reactivity for a regenerable heavy metal sorbent. *Langmuir* **2012**, *28*, 3931–3937. [[CrossRef](#)] [[PubMed](#)]
128. Wu, Z.; Gu, Z.; Wang, X. Effects of organic acids on adsorption of lead onto montmorillonite, goethite and humic acid. *Environ. Pollut.* **2003**, *121*, 469–475. [[CrossRef](#)]
129. Bhattacharyya, K.G.; Gupta, S.S. Adsorptive accumulation of Cd (II), Co (II), Cu (II), Pb (II), and Ni (II) from water on montmorillonite: Influence of acid activation. *J. Colloid Interface Sci.* **2007**, *310*, 411–424. [[CrossRef](#)] [[PubMed](#)]
130. Yin, J.; Jiang, Z.; Chang, G. Simultaneous on-line preconcentration and determination of trace metals in environmental samples by flow injection combined with inductively coupled plasma mass spectrometry using a nanometer-sized alumina packed micro-column. *Anal. Chim. Acta* **2005**, *540*, 333–339. [[CrossRef](#)]
131. Al-Degs, Y.; Khraisheh, M.A.M.; Tutunji, M.F. Sorption of lead ions on diatomite and manganese oxides modified diatomite. *Water Res.* **2001**, *35*, 3724–3728. [[CrossRef](#)]
132. Rivera-Utrilla, J.; Bautista-Toledo, I.; Ferro-García, M.A. Activated carbon surface modifications by adsorption of bacteria and their effect on aqueous lead adsorption. *J. Chem. Technol. Biotechnol.* **2001**, *76*, 1209–1215. [[CrossRef](#)]
133. Herrera-Urbina, R.; Sotillo, F.J.; Fuerstenau, D.W. Amyl xanthate uptake by natural and sulfide-treated cerussite and galena. *Int. J. Miner. Process.* **1998**, *55*, 113–128. [[CrossRef](#)]
134. Han, G.; Wen, S.M.; Wang, H.; Feng, Q.C. Sulfidization regulation of cuprite by pre-oxidation using sodium hypochlorite as an oxidant. *Int. J. Min. Sci. Technol.* **2021**, *31*, 1117–1128. [[CrossRef](#)]
135. Cui, K.; He, Y.; Jin, S. Enhanced UV-visible response of bismuth subcarbonate nanowires for degradation of xanthate and photocatalytic reaction mechanism. *Chemosphere* **2016**, *149*, 245–253. [[CrossRef](#)] [[PubMed](#)]
136. Molina, G.C.; Cayo, C.H.; Rodrigues, M.A.S. Sodium isopropyl xanthate degradation by advanced oxidation processes. *Miner. Eng.* **2013**, *45*, 88–93. [[CrossRef](#)]
137. Chen, S.; Gong, W.; Mei, G. Primary biodegradation of sulfide mineral flotation collectors. *Miner. Eng.* **2011**, *24*, 953–955. [[CrossRef](#)]
138. Wang, J.; Zhuan, R. Degradation of antibiotics by advanced oxidation processes: An overview. *Sci. Total Environ.* **2020**, *701*, 135023. [[CrossRef](#)] [[PubMed](#)]
139. Zhou, P.; Shen, Y.; Zhao, S. Synthesis of clinoptilolite-supported BiOCl/TiO₂ heterojunction nanocomposites with highly-enhanced photocatalytic activity for the complete degradation of xanthates under visible light. *Chem. Eng. J.* **2021**, *407*, 126697. [[CrossRef](#)]
140. Wu, S.; Hu, H.; Lin, Y. Visible light photocatalytic degradation of tetracycline over TiO₂. *Chem. Eng. J.* **2020**, *382*, 122842. [[CrossRef](#)]
141. Zeng, Q.; Xie, X.; Wang, X. Enhanced photocatalytic performance of Ag@TiO₂ for the gaseous acetaldehyde photodegradation under fluorescent lamp. *Chem. Eng. J.* **2018**, *341*, 83–92. [[CrossRef](#)]
142. Feizpoor, S.; Habibi-Yangjeh, A.; Ahadzadeh, I. Oxygen-rich TiO₂ decorated with C-Dots: Highly efficient visible-light-responsive photocatalysts in degradations of different contaminants. *Adv. Powder Technol.* **2019**, *30*, 1183–1196. [[CrossRef](#)]
143. Feizpoor, S.; Habibi-Yangjeh, A.; Yubuta, K. Integration of carbon dots and polyaniline with TiO₂ nanoparticles: Substantially enhanced photocatalytic activity to removal various pollutants under visible light. *J. Photochem. Photobiol. A Chem.* **2018**, *367*, 94–104. [[CrossRef](#)]
144. Liu, S.; Lim, M.; Amal, R. TiO₂-coated natural zeolite: Rapid humic acid adsorption and effective photocatalytic regeneration. *Chem. Eng. Sci.* **2014**, *105*, 46–52. [[CrossRef](#)]
145. Shen, Y.; Zhou, P.; Zhao, S. Synthesis of high-efficient TiO₂/clinoptilolite photocatalyst for complete degradation of xanthate. *Miner. Eng.* **2020**, *159*, 106640. [[CrossRef](#)]
146. Bian, Z.; Feng, Y.; Li, H. Fabrication of Ag₃PO₄/TiO₂@ molecular sieve (MS) ternary composites with remarkably enhanced visible light-responded photocatalytic activity and mechanism insight. *Environ. Res.* **2020**, *190*, 109984. [[CrossRef](#)] [[PubMed](#)]
147. Bi, X.; Du, G.; Kalam, A. Constructing anatase TiO₂/Amorphous Nb₂O₅ heterostructures to enhance photocatalytic degradation of acetaminophen and nitrogen oxide. *J. Colloid Interface Sci.* **2021**, *601*, 346–354. [[CrossRef](#)] [[PubMed](#)]
148. Wei, G.T.; Fan, C.Y.; Zhang, L.Y. Photo-Fenton degradation of methyl orange using H₃PW₁₂O₄₀ supported Fe-bentonite catalyst. *Catal. Commun.* **2012**, *17*, 184–188. [[CrossRef](#)]
149. Zhang, L.Y.; Cai, S.Y.; Huang, K. Preparation of H₃PMo₁₂O₄₀/organobentonite by chemical immobilization method and its catalytic performance in photo-Fenton process. *Desalin. Water Treat.* **2013**, *51*, 7815–7824. [[CrossRef](#)]
150. Fu, L.; Zhao, Z.; Ma, J. Cavity-confined acceleration of iron cycle for the Fenton-like reaction by β-CD-benzoquinone host–guest complex under visible irradiation. *Catal. Commun.* **2015**, *65*, 96–101. [[CrossRef](#)]
151. Wang, S. A comparative study of Fenton and Fenton-like reaction kinetics in decolourisation of wastewater. *Dyes Pigments* **2008**, *76*, 714–720. [[CrossRef](#)]
152. Lee, H.; Shoda, M. Removal of COD and color from livestock wastewater by the Fenton method. *J. Hazard. Mater.* **2008**, *153*, 1314–1319. [[CrossRef](#)]
153. Zhao, H.; Cao, J.; Lv, H. 3D nano-scale perovskite-based composite as Fenton-like system for efficient oxidative degradation of ketoprofen. *Catal. Commun.* **2013**, *41*, 87–90. [[CrossRef](#)]
154. Trabelsi-Souissi, S.; Oturan, N.; Bellakhal, N. Application of the photo-Fenton process to the mineralization of phthalic anhydride in aqueous medium. *Desalin. Water Treat.* **2011**, *25*, 210–215. [[CrossRef](#)]
155. Xu, T.; Zhu, R.; Zhu, G. Mechanisms for the enhanced photo-Fenton activity of ferrihydrite modified with BiVO₄ at neutral pH. *Appl. Catal. B Environ.* **2017**, *212*, 50–58. [[CrossRef](#)]

156. Men, L.; Zhou, Y.; Guo, H. Experimental study on treating cellulose acetate wastewater based on electro-Fenton. In Proceedings of the 2018 7th International Conference on Energy, Environment and Sustainable Development (ICEESD 2018), Shenzhen, China, 30–31 March 2018.
157. Ai, G.; Tao, X.; Wang, Y. Removal of xanthate in flotation wastewater by ultrasound and Fenton reagent. In Proceedings of the 2011 International Conference on Electric Technology and Civil Engineering (ICETCE), Lushan, China, 22–24 April 2011.
158. Liu, Q.; Liu, S.; Yang, M. Application of Fenton reagent in the treatment for kaolin processing waste water. *J. Saf. Environ.* **2006**, *1*, 74–75.
159. Zhang, L.; Wei, X. The degradation of pyridine in aqueous solution by the ultrasound/Fenton reagent. *Environ. Chem.* **2009**, *3*, 365–366.
160. Zhou, J.J.; Yuan, F.Y.; Wang, G.J. Experimental Research on the Treatment of RDX Wastewater by US/Fenton Reagent. *Shanghai Chem. Ind.* **2009**, *34*, 11–14.
161. Zhao, D.; Zhan, C.; Jin, X. Study on degradation of p-nitrophenol in aqueous solution by ultrasound-Fenton reagent technology. *J. Zhejiang Univ. Technol.* **2004**, *32*, 311–315.
162. García-Leiva, B.; Teixeira, L.A.C.; Torem, M.L. Degradation of xanthate in waters by hydrogen peroxide, fenton and simulated solar photo-fenton processes. *J. Mater. Res. Technol.* **2019**, *8*, 5698–5706. [[CrossRef](#)]
163. Yang, Y.; Zhang, L.; Zhu, Y. Three-dimensional photoelectrocatalytic degradation of ethyl xanthate catalyzed by activated bentonite-based bismuth ferrites particle electrodes: Influencing factors, kinetics, and mechanism. *J. Environ. Chem. Eng.* **2021**, *9*, 105559. [[CrossRef](#)]
164. Catrinescu, C.; Teodosiu, C.; Macoveanu, M. Catalytic wet peroxide oxidation of phenol over Fe-exchanged pillared beidellite. *Water Res.* **2003**, *37*, 1154–1160. [[CrossRef](#)]
165. Feng, J.; Hu, X.; Yue, P.L. Discoloration and mineralization of Reactive Red HE-3B by heterogeneous photo-Fenton reaction. *Water Res.* **2003**, *37*, 3776–3784. [[CrossRef](#)]
166. Feng, J.; Hu, X.; Yue, P.L. Novel bentonite clay-based Fe-nanocomposite as a heterogeneous catalyst for photo-fenton discoloration and mineralization of orange II. *Environ. Sci. Technol.* **2004**, *38*, 269–275. [[CrossRef](#)] [[PubMed](#)]
167. Soon, A.N.; Hameed, B.H. Heterogeneous catalytic treatment of synthetic dyes in aqueous media using Fenton and photo-assisted Fenton process. *Desalination* **2011**, *269*, 1–16. [[CrossRef](#)]
168. Wei, G.; Li, Y.; Cai, S. Photo-Fenton degradation of ethyl xanthate catalyzed by bentonite-supported Fe (II)/phosphotungstic acid under visible light irradiation. *Water Sci. Technol.* **2018**, *2017*, 473–480. [[CrossRef](#)]
169. Shao, L.; Wei, G.; Wang, Y. Preparation and application of acidified/calcined red mud catalyst for catalytic degradation of butyl xanthate in Fenton-like process. *Environ. Sci. Pollut. Res.* **2016**, *23*, 15202–15207. [[CrossRef](#)] [[PubMed](#)]
170. Chen, S.; Du, D. Degradation of n-butyl xanthate using fly ash as heterogeneous Fenton-like catalyst. *J. Cent. South Univ.* **2014**, *21*, 1448–1452. [[CrossRef](#)]
171. Park, J.H.; Han, Y.S.; Ji, S.W. Investigation of Mineral-Processing Wastewater Recycling Processes: A Pilot Study. *Sustainability* **2018**, *10*, 3069. [[CrossRef](#)]
172. Rao, S.R.; Finch, J.A. A review of water re-use in flotation. *Miner. Eng.* **1989**, *2*, 65–85. [[CrossRef](#)]
173. Akhoundi, A.; Nazif, S. Sustainability assessment of wastewater reuse alternatives using the evidential reasoning approach. *J. Clean. Prod.* **2018**, *195*, 1350–1376. [[CrossRef](#)]
174. Shengo, L.M.; Mutiti, W.N.C. Bio-treatment and water reuse as feasible treatment approaches for improving wastewater management during flotation of copper ores. *Int. J. Environ. Sci. Technol.* **2016**, *13*, 2505–2520. [[CrossRef](#)]
175. Farrokhpay, S.; Zanin, M. An investigation into the effect of water quality on froth stability. *Adv. Powder Technol.* **2012**, *23*, 493–497. [[CrossRef](#)]