International Journal of Applied and Natural Sciences
ISSN: 3005-3471
DOI: 10.61424/ijans
Journal Homepage: www.bluemarkpublishers.com/index.php/IJANS

IJANS
BLUEMARK PUBLISHERS

| RESEARCH ARTICLE

A Critical Review of Ion Flotation as a Sustainable Wastewater Treatment Technique: Scope, Efficiency, and Application

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| ABSTRACT
Ion flotation has developed as an important technology for selectively removing heavy metal ions from contaminated aquatic environments, including wastewater. This review meticulously analyzes the foundational principles, advancements, and practical implementations of ion flotation, with an emphasis on its efficacy, operational flexibility, and sustainability. The paper explores various flotation approaches, including conventional ion flotation, precipitate flotation, and hybrid sorptive and biosorptive systems, shedding light on their underlying mechanics, performance metrics, and operational variables. Prior studies show that optimizing conditions can result in removal rates over 90% for pollutants like Pb^{2+}, Cd^{2+}, Cu^{2+}, and Zn^{2+}. Innovations in surfactant chemistry, Nano-enhanced collectors, and bio-sorbents have augmented selectivity, reduced chemical consumption, and bolstered environmental compatibility. Precipitate flotation demonstrates enhanced efficacy in multi-metal systems, while biosorptive flotation presents economical and ecologically sustainable alternatives. Nonetheless, obstacles such as collector recovery, foam stability, and challenges associated with scale-up persist as substantial impediments. This analysis finds that ion flotation, particularly in its advanced and hybridized forms, has significant potential for integration into sustainable wastewater treatment paradigms. Future inquiries should emphasize pilot-scale validation, system integration, and life-cycle analysis to facilitate broader industrial applicability and alignment with the objectives of a circular economy.

| KEYWORDS

Ion flotation, Heavy metal removal, Wastewater treatment, Precipitate flotation, Sorptive flotation, Biosorptive flotation

| ARTICLE INFORMATION

ACCEPTED: 11 April 2025 **PUBLISHED:** 28 June 2025 **DOI:** 10.61424/ijans.v3.i2.344

1. Introduction
The term "heavy metals" lacks a consistent definition across different contexts (Fei & Hu, 2023). When defined by density, heavy metals refer to metallic elements that possess a density greater than 4 or 5 g cm^{-3} (Duruibe et al., 2007; Fei & Hu, 2023; Järup, 2003; Srivastava & Majumder, 2008). In relation to environmental concerns, heavy metals refer to metal (and metalloid) compounds that tend to be non-biodegradable, bio-accumulative, and carcinogenic (Fei & Hu, 2023), which include elements like arsenic (Ar), cadmium (Cd), chromium (Cr), cobalt (Co), copper (Cu), iron (Fe), lead (Pb), manganese (Mn), mercury (Hg), nickel (Ni), silver (Ag), and zinc (Zn) (Duruibe et al., 2007; Järup, 2003). The elimination of heavy metal ions is critically important because of their significant toxicity (Yuan et al., 2008).

At present, there are various treatment methods and approaches available for extracting heavy metal ions from water solutions (Yuan et al., 2008). The most widely used is chemical precipitation, which itself is relatively simple (Ogbodo et al., 2023), but the way of removing generated sludge is a frequently encountered problem (Yuan et al., 2008). Alternative processes commonly used include ion exchange, membrane filtration, adsorption, and reverse osmosis, all of which can generate drinking water (Schlebusch et al., 2023). However, these techniques often face challenges such as high costs (Uzochukwu, Kanwulia, et al., 2025), significant energy demands, the production of secondary pollutants, or limited efficiencies when dealing with large volumes of diluted solutions, which hinders their implementation (Chai et al., 2021; Dias et al., 2007; Fu & Wang, 2011; Liu & Doyle, 2001; Mishra et al., 2021) . The waste byproducts generated from these treatment methods are rarely subjected to metal recovery processes (L. Emembolu et al., 2020) and are generally treated at the end of the pipeline before being disposed of in landfills by licensed waste management companies (Heuss-Aßbichler et al., 2016).

Ion flotation was suggested as a method in the early 1960s (Lynch et al., 2007), and it has been demonstrated to be an effective technique for extracting metals from large quantities of dilute aqueous solutions (cMe ≤ 1 × 10−4 mol/L) (Chang et al., 2019; Yuan et al., 2008). In ion flotation, an ionic collector is employed to move non-surface active colligend ions with the opposite charge from the bulk solution to the solution-vapor interface (Yuan et al., 2008). During this process, surfactants serve the dual functions of collector and frother, aiding in the adhesion of the colligend species to the surface of an air bubble (Yuan et al., 2008). When compared to traditional physicochemical separation methods (L. N. Emembolu et al., 2021; C. N. Onyenanu et al., 2023), ion flotation is straightforward to operate and can be viewed as a cost-effective solution (Yuan et al., 2008). Ion flotation was primarily utilized for the pre-concentration of precious metals from low-concentration solutions (Chang et al., 2019). To the present day, this ion flotation technique has been extended to applications in wastewater and water treatment (Chang et al., 2019; Ghazy et al., 2008), recovery of precious metals (Chang et al., 2019; Hernández-Expósito et al., 2006), pre-concentrating rare earth elements (D. E. Chirkst et al., 2009), and the selective separation of multiple ionic components (Chang et al., 2019; D. Chirkst et al., 2011). Numerous flotation methods exist, such as ion flotation, precipitative flotation, sorptive flotation, dissolved air flotation, and foam fractionation (Schlebusch et al., 2023). Nevertheless, the choice of method should be based on the characteristics of the upstream solution, the desired quality of the treated solution, and the chemistry of the solution (Heuss-Aßbichler S. et al., 2016; Schlebusch et al., 2023).

This review provides a critical analysis of the potential of ion flotation as an eco-friendly method for treating wastewater (Wan Nafi & Taseidifar, 2022), focusing on its range, effectiveness in removal, and adaptability in applications (Chang et al., 2019; Deliyanni et al., 2017). The objective of the review is to consolidate recent research developments (C. Onyenanu & Emembolu, 2020), identify essential operational factors (Vilochani et al., 2024), and evaluate its practicality for selectively separating metals in intricate water mixtures (C. Onyenanu & Nnanyelum, 2020). In doing so, it aims to guide future advancements and encourage a wider implementation of ion flotation within environmental cleanup strategies.

2. Description of Ion Flotation

Ion flotation, initially introduced by Sebba, (1959) and further explored by Sebba, (1962), is an emerging separation method for extracting and eliminating metal ions from dilute aqueous solutions (Arslan & Bulut, 2022; Doyle, 2003; Zamboulis et al., 2011). It is a gravity separation technique that undoubtedly originated from the processing of minerals, specifically known as froth flotation, with common applications in the treatment of sulphide minerals (Deliyanni et al., 2017). In this technique, a collector, which is an ionic surface-active reagent, is introduced into the target solution and adsorbs at the interface between the solution and vapor (Doyle, 2003; Sun et al., 2022) as illustrated in Figure 1. For charge neutrality, counter ions must also be co-adsorbed (Doyle, 2003). If the surfactant has a stronger interaction with the non-surface-active ions of interest (colligend) than with the originally associated ions (e.g., H+, Na+, NH4+), it will preferentially adsorb the colligend alongside the surfactant, either electrically or chemically (Doyle, 2003). Suitable surfactants, whether as the collector or as a separate frother, will help prevent bubble rupture and facilitate foam formation (John et al., 2025). The significance of flotation to the global industrial economy is regarded as immense (Dehghani et al., 2016; Deliyanni et al., 2017; Kyzas & Matis, 2016; Li et al., 2015; Shah, 2016). Without this separation method, numerous well-known metals and inorganic raw materials would be extremely limited and expensive (Uzochukwu, Ezechukwu, et al., 2025), as the high-quality ores that could be extracted using straightforward physical and mechanical techniques have long ago been depleted (Deliyanni et al., 2017).

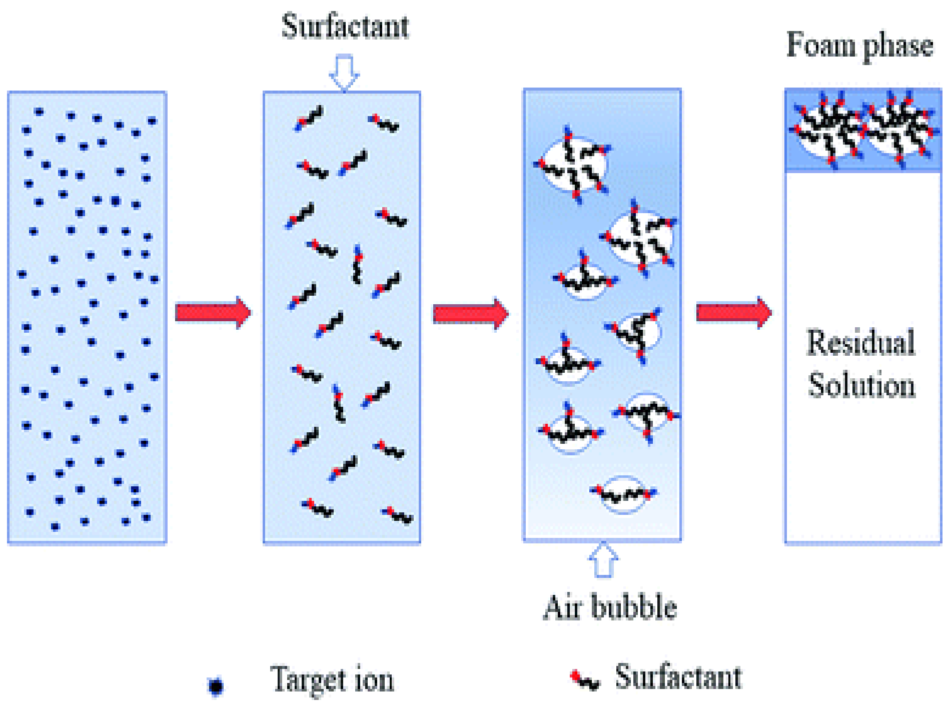

Figure 1: Schematic of the overall process of ion flotation (Chang et al., 2019)

Ion flotation has been conducted in other studies to explore the key factors and kinetics involved in the removal of Zn(II) ions from wastewater (Hoseinian et al., 2017; Kyzas & Matis, 2018). The ideal conditions were initially identified through experiments performed in a Hallimond tube. The same research team also examined the ion flotation process for nickel ions (Hoseinian et al., 2018). This removal process was assessed using various parameters, such as chemical interactions, water retention in the froth phase, the separation mechanism, and the rate of Ni(II) removal . A significant older study done by Rubin & and Lapp, (1971) linked the hydrolytic behavior of a metal (specifically zinc) to its removal through foaming. The findings indicated that precipitate flotation at a pH level exceeding 8, where zinc is no longer considered an insoluble hydroxide, proved to be a more effective removal method than foaming for soluble metal species.

The standard laboratory setup, illustrated in Figure 2, typically comprises a conditioning/feed tank equipped with a mechanical mixer, a peristaltic pump, liquid rotameters, a flotation column featuring a weir at the top, a foam collection tank, an air compressor connected via a needle valve, a washing trap and air flowmeter, a porous diaphragm located at the cell's bottom, a mercury U-tube manometer, an effluent tank, a pH meter, and a chemical dosing pump. For hydrodynamic considerations, counter-current operation is preferred (Kyzas & Matis, 2018; Peleka & Matis, 2016).

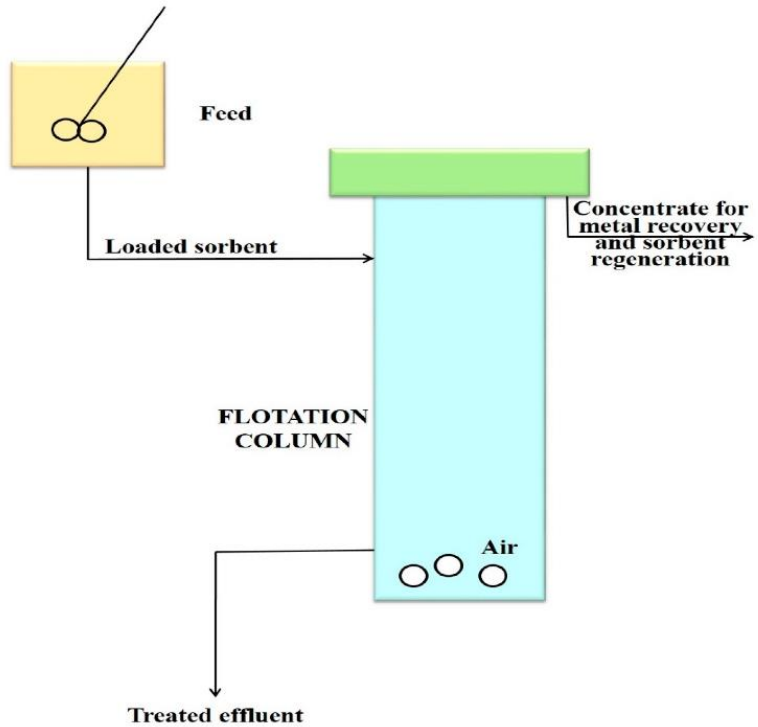

Figure 2. Scheme of a counter-current dispersed-air flotation rig (Kyzas & Matis, 2018)

3. Applications of Ion Flotation in Wastewater Treatment

Ion flotation has proven effective in processing various industrial wastewaters that contain heavy metal pollutants (John et al., 2025; Uzochukwu et al., 2025; Godspower et al., 2024). The following is a summary of significant applications, emphasizing actual and synthetic wastewater systems, types of collectors/surfactants, operational conditions, and results.

Table 1. Summary of Ion Flotation Applications in Wastewater Treatment

S/N	Target Ion(s)	Collector/Surfactant	Matrix / Conditions	Efficiency (%)	Reference
1	Pb^{2+}	SDS + barley husk	Industrial wastewater, pH ~5.5	>95%	(Mohammed et al., 2013)
2	Cd^{2+}	SDS	Synthetic wastewater, low initial conc.	>90%	(Hong et al., 2016)
3	Cu^{2+}, Zn^{2+}, Cr^{3+}	SDS or CTAB	Electroplating effluent, low pH	~90%	(Polat & Erdogan, 2007)
4	Cu^{2+}	Silica nanoparticles (SNP)	Ultra-trace Cu^{2+} from industrial wastewater	>92%	(Hu et al., 2017)
5	Cd^{2+}, Pb^{2+}, Cu^{2+}	Tea saponin (biosurfactant)	Synthetic mixture of heavy metals	71–90%	(Yuan et al., 2008)
6	Cr(VI)	SDS	Tannery wastewater	>85%	(Chang et al., 2019)
7	Ni^{2+}	MWCNTs + frother	Industrial effluent, flotation-adsorption hybrid	88–95%	(Dehghani et al., 2017)
8	Ga^{3+}, Al^{3+}	SDS	Mixed-metal synthetic solution	Selective removal	(Zahra et al., 2017)
9	Cu^{2+}	Dodecylbenzene sulfonate (DBS)	Leachate with organic content	91–93%	(Bernasconi et al., 1988)
10	Cd^{2+}	Classical ion flotation	Lab column (R&D setup)	~88%	(Scorzelli et al., 1999)

Table 1 showcases a variety of research studies that focus on the use of ion flotation to eliminate different heavy metal ions from both synthetic and real wastewater samples. A thorough assessment of these results highlights significant patterns in process effectiveness, operational adaptability, and innovative materials, alongside enduring challenges. One notable aspect across the examined studies is the consistently high removal efficiency reported for critical hazardous metals like Pb^{2+}, Cd^{2+}, Cu^{2+}, and Zn^{2+}. For example, Mohammed et al. (2013) achieved more than 95% removal of Pb^{2+} by utilizing sodium dodecyl sulfate (SDS) along with a biosorbent, indicating the potential of hybrid flotation–adsorption systems to improve performance. Dehghani et al. (2017) and Hu et al. (2017) observed similar trends, where multi-walled carbon nanotubes and silica nanoparticles served as effective high-surface-area carriers, facilitating the efficient pre-concentration and flotation of metal ions such as Ni^{2+} and Cu^{2+}.

Another important finding is the dependability of SDS and CTAB as collectors under varying metal species and wastewater conditions. These surfactants possess favorable surface activity and ion-binding capabilities, allowing for the flotation of both mono- and multi-valent metal ions. Nonetheless, Yuan et al. (2008) showed that the growing interest in biosurfactant-based flotation can be explained by the persistent and hazardous environmental effects of synthetic surfactants. Biosurfactants like tea saponins provide an eco-friendlier option, achieving respectable removal efficiencies (71–90%), although their application may require larger dosages and present challenges in terms of foaming stability and cost. From an operational perspective, managing pH is a crucial element that impacts flotation effectiveness. Many systems functioned optimally within slightly acidic to neutral pH ranges, which align with the best conditions for surfactant-ion interaction and favorable metal speciation. For instance, Polat and Erdogan (2007) fine-tuned flotation at reduced pH levels for electroplating wastewater, emphasizing how the chemistry of wastewater should guide the selection of collectors and flotation setups. Additionally, it is noteworthy that there is a trend towards selective flotation in complex ionic mixtures. Zahra et al. (2017) illustrated the separation of Ga^{3+} from Al^{3+} using SDS, highlighting the adaptability of the method for the recovery of strategic and rare earth elements from dilute solutions. Although this selective behavior is beneficial, it still encounters challenges under competitive adsorption circumstances, where multiple ions compete for collector association.

4. Performance and Efficiency

Ion flotation methods show significant variability in effectiveness, heavily dependent on factors such as flotation type, ion species, collector chemistry, pH, and hydrodynamic conditions. This section examines the removal efficiency, selectivity, kinetics, and operational feasibility of both ion and precipitate flotation compared to sorptive and biosorptive flotation systems, drawing on previous research.

4.1 Ion & Precipitate Flotation

Ion flotation and precipitate flotation are traditional methods that have been refined through the enhancement of collector chemistry and operational conditions. These techniques are particularly efficient for extracting heavy metals such as Cu^{2+}, Zn^{2+}, Cd^{2+}, and Fe^{3+} from both synthetic and industrial wastewater. Precipitate flotation generally involves creating hydroxide or sulfide precipitates, which are then floated using surfactants or frothers. The effectiveness of these systems, including their removal efficiency and operational parameters, is summarized in Table 2, which gathers findings from significant studies showing their efficiencies.

Table 2: Performance Metrics of Ion and Precipitate Flotation for Heavy Metal Removal from Aqueous Systems

Study Title	Key Findings	Author(s) and Date
Removal of Fe(III), Cd(II), and Zn(II) as Hydroxides by Precipitation–Flotation System	"The results showed that 99% efficiency was attained from a mixture solution containing the three metal ions in sulfate media at pH 10.3 after 15 min of treatment. The sedimentation behavior showed that a larger precipitate facilitated solid/liquid separation at 30 min. The results provide evidence of the effectiveness of the removal of metal ions by the combined precipitation–flotation system as an alternative for the treatment of acid mine drainage (AMD) in less time in comparison with a sedimentation stage."	(Zapién Serrano et al., 2021)
Removal of Cadmium (II) from Aqueous Solution by Ion Flotation Using Rhamnolipid Biosurfactant As an Ion Collector	"The maximum removals of Cd from clean and Zn- and Cu-contaminated solutions were about 57%, 36%, and 48%, respectively. Kinetic studies indicated that ion flotation of cadmium follows a first-order equation with a kinetic rate of 0.0071 min^{-1}. Although the removals are rather low, it seems that the use of rhamnolipid biosurfactant can be promising in heavy-metal removal from wastewaters by foam flotation with some modifications."	(Bodagh et al., 2013)
Removal of Fe (III), Cd (II), and Zn (II) as Hydroxides by Precipitation–Flotation System	"Goethite has proved to be effective for the removal of chromium (VI) and zinc ions. Also, adsorbing colloid flotation with ferric hydroxide (as the co-precipitant) could be an alternative method to the above-mentioned separation of metal ions. In both cases, chromium (VI) (pH=4) and zinc (pH=7) removal was about 100%. The reasons for selecting the iron-based bonding materials, like goethite and/or in-situ produced ferric hydroxide, are that they are cheap, easily synthesized, suitable both for cation and anion sorption, and that they present low risks for adding a further pollutant to the system."	(Deliyanni et al., 2004)
Flotation and Sorptive-Flotation Methods for Removal of Lead Ions from Wastewater Using SDS as Surfactant and Barley Husk as Biosorbent	"The results show that the removal efficiency was enhanced by about 10% when using sorptive-flotation compared with flotation only under the same conditions."	(Mohammed et al., 2013)
Simultaneous Removal of Al, Cu, and Zn Ions from Aqueous Solutions Using Ion and Precipitate Flotation Methods	"The results indicate that satisfying simultaneous flotations of aluminum, copper, and zinc species are observed if the pH value ranges between 7.0 and 9.0. It was found that an increase in collector concentration results in a decrease in the flotation rate constants. An increase in the gas velocity results in an increase in the ion and precipitate flotation rates."	(Rybarczyk & Kawalec-Pietrenko, 2021)
An efficient separation for metal ions from wastewater by ion precipitate flotation: Probing formation and growth evolution of metal-reagent flocs	"The flotation results of MHA-Fe-CTAB are as follows: flotation removal of 98.7 ± 0.40%–99.9 ± 0.10%, residual TOC of 0.96 ± 0.38–1.35 ± 0.41 mg/L, and turbidity of 0.44 ± 0.09–0.63 ± 0.16 NTU. Introducing $Fe3+$ and CTAB reagents into flotation solution contributes to the growth-evolution of precipitate flocs, which could intensify the metal-ions removal via the precipitate flotation process and result in more ideal purification indexes for metal-containing wastewater."	(Wu et al., 2021)
Heavy metal removal from waste waters by ion flotation	"Metal removal reached about 74% under optimum conditions at low pH. At basic pH, it became as high as 90%, probably due to the contribution from the flotation of metal precipitates."	(Polat & Erdogan, 2007)
Ion flotation and its applications in the concentration, recovery, and removal of metal ions from solutions	"This method gives very successful and promising results in removing heavy metals with toxic effects from wastewater and selective separation of metal ions from very low concentrated solutions. Ion flotation may take place in industrial-scale operations with the new developments in flotation machines and collectors with better selectivity, high efficiency, lower cost, and environmental friendliness."	(Arslan & Bulut, 2022)
Toxic heavy metal ions removal from wastewater by ion flotation using a nano collector	"Under the optimum chemical and hydrodynamic conditions, using functionalized graphene oxide (FGO) with much lower concentration than stoichiometry concentration resulted in the maximum removal of lead,	(Hoseinian et al., 2023)

	copper, nickel, cadmium, and zinc ions with percentages of 97.07, 99.02, 98.38, 95.20, and 98.94, respectively. In optimum condition, water recovery was 8 %. The use of FGO in the ion flotation process for wastewater treatment offered significant benefits, including high adsorption efficiency, low collector consumption, recyclability, and the absence of critical micelle concentration (CMC) and frothing properties."	
Removal of cadmium (II) from simulated wastewater by the ion flotation technique	"The best removal efficiency obtained at a collector-metal ratio of 3:1 in 60 min with a flow rate of 150 mL/min was 84%. The maximum cadmium removal was 92.1%, where ethanol was introduced at a concentration of 0.4% to the flotation column with the above conditions. The obtained results were promising, as both cadmium and the collector were effectively removed from the wastewater. Hence, the application of ion flotation for metal ions removal from effluents seems to be efficient."	(Salmani et al., 2013)
Synthesis and characterization of a novel nanocollector for the removal of nickel ions from synthetic wastewater using ion flotation	"This study introduced a new collector for ion flotation to reduce the required collector concentration during the process, which had simple synthesis, was economical, had high efficiency, and stability in wastewater. The nickel removal percentage of approximately 100% was achieved using the nanocollector."	(Hoseinian et al., 2020)
Removal of heavy metal ions from water using ion flotation	"Re-crystallized octanoyl-cysteine (octanoyl-cys) surfactant showed the highest removal efficiency at 99.9% for Hg ions, using pure nitrogen gas. Successful removal results of most other ions were found to be in the range 99.1–99.7%, using either air or nitrogen gas."	(Taseidifar et al., 2017)
Removal of rhodamine B (a basic dye) and thoron (an acidic dye) from dilute aqueous solutions and wastewater simulants by ion flotation	"The results obtained are discussed concerning dissociation of dye, type of collector, ionic strength, and sign and magnitude of charge of added foreign ions. Kinetics of flotation were also studied. Further studies demonstrate that under optimum conditions, the developed flotation processes can be applied for the treatment of dye-contaminated wastewaters simulated to those generated at dyeing industries and radiochemical laboratories."	(Shakir et al., 2010)
Evaluation of tea-derived biosurfactant on removing heavy metal ions from dilute wastewater by ion flotation	"The foam products were identified by Fourier transform infrared (FTIR) spectroscopy, and the result indicated that the carboxylate groups and divalent metal ions formed a definite complexation in the bulk solution."	(Yuan et al., 2008)
Comprehensive evaluation on a prospective precipitation-flotation process for metal ions removal from wastewater simulants	"The results reveal that metal-ions chelate with humics at low metal-ion concentration, generating the limited micro-size precipitates of <2.0 μm, fractal dimension of 1.60–1.80, and precipitate efficiency of <91.00%. The flotation removal of metal ions from single or mixed solutions is respectively 99.10 ± 0.10% for Cu2+, 99.60 ± 0.10% for Pb2+, and 94.30 ± 0.30% for Zn2+. Therefore, the enhanced precipitation flotation process is an efficient purification approach for metal-containing wastewaters."	(Wu et al., 2019)
Removal of Zn Ions from Synthetic Wastewater Using Graphene Oxide as a Nanocollector in Ion Flotation	"Under optimal conditions (pH 8.5, GO concentration 40 mg/L, SDS concentration 37.5 mg/L, air flow rate 2 L/min, and impeller speed 800 rpm), Zn ion removal and water recovery reached 90% and 36%, respectively."	(Sobouti et al., 2024)
Effect of impeller speed on the Ni(II) ion flotation	"The results show that the Ni(II) removal increases with increasing impeller speed from 600 to 800 rpm, from less than 41% to 88%, respectively, and after that, it decreases to 79% with increasing impeller speed to 900 rpm in the first 4 min of flotation."	(Hoseinian et al., 2019)

Ion and precipitate flotation are highly effective in removing multivalent metal ions, especially under optimized pH and collector conditions. Classical ion flotation, using collectors like SDS or CTAB, often exceeds 90% removal efficiency for Cu^{2+}, Zn^{2+}, and Cd^{2+} (Polat & Erdogan, 2007). Precipitate flotation typically involves hydroxide or sulfide formation prior to flotation, enhancing selectivity and reducing surfactant demand. For instance, Zapién Serrano et al. (2021) reported up to 99% removal of Fe^{3+}, Cd^{2+}, and Zn^{2+} through hydroxide precipitation at pH 10.3, followed by flotation. Wu et al. (2021) highlighted that introducing Fe^{3+} and CTAB contributed to superior floc evolution and flotation, achieving removal efficiencies over 99%. Similarly, Deliyanni et al. (2004) utilized ferric hydroxide as a co-precipitant, achieving near-total Cr(VI) and Zn^{2+} removal under acidic and neutral conditions, respectively.

Despite its effectiveness, the main limitations include sludge handling, pH sensitivity, and the competition between metal ions for collectors. However, recent advancements like nano-collector introduction (e.g., functionalized graphene oxide, FGO) have addressed many challenges by lowering required dosages and improving selectivity (Hoseinian et al., 2023).

4.2 Sorptive and Biosorptive Flotation

Techniques such as sorptive and biosorptive flotation provide improved selectivity and sustainability by combining adsorption with flotation processes (Ekwueme et al., 2023; Ajali, Umenwa, et al., 2023; Onyenanu & Emembolu, 2020). These methods make use of a variety of natural or synthetic sorbents—like biomass, graphene oxide, or waste materials from agriculture—as carriers for heavy metal ions (Ajali & Onyenanu, 2023; Ajali, Victor, et al., 2023). Biosurfactants or affordable biosorbents serve both as collectors and stabilizers, achieving high removal efficiencies with minimal environmental harm. As illustrated in Table 3, many studies demonstrate removal efficiencies exceeding 85% for metals such as Pb^{2+}, Ni^{2+}, and Cu^{2+}, confirming the effectiveness of these methods for environmentally friendly wastewater treatment solutions.

Table 3: Efficiency of Sorptive and Biosorptive Flotation Techniques Using Various Collectors and Sorbents

Study Title	Key Findings	Author(s) and Date
Removal of Nickel and Cadmium Ions from Wastewater by Sorptive Flotation: Single and Binary Systems	"The sorption process, which is PH dependent, shows maximum removal of metal ions at pH 7. Langmuir and Freundlich isotherm expressions were found to give a good fit to the experimental data. Kinetic data correlated well with the Lagergren second-order kinetic model, and the flotation step enhanced the removal efficiency of nickel and cadmium from wastewater from about 75% to 94%, and reduced turbidity, so it can dispense with the filtering process, which is an expensive technology. It is believed that flotation separation has great potential as a clean water and wastewater treatment technology."	(Mohammed & Mohammed, 2014)
The use of Artificial Neural Network (ANN) for modeling Cu (II) ion removal from aqueous solution by flotation and sorptive flotation process	"The best value of these parameters that achieved maximum removal efficiency of Cu(II) ion were 30 g/l initial Cu(II) ion concentration, 500 cm3/min flow rate for both systems and 7 g/l sunflower seed husk for sorptive flotation while the SDS concentration was 60 mg/L for flotation and 30 mg/L for sorptive flotation. The linear regression between the corresponding targets and network outputs was confirmed to be satisfactory, with a correlation coefficient of 0.99955 and 0.99549 in flotation and sorptive flotation systems, respectively. Sensitivity analysis shows that the time and pH were found to be the most significant parameters of relative importance 24.22 and 23.02% in the flotation system, and the sunflower seed husk dosage and time with relative importance of 26.86 and 24.23% were found to be the most affected ones for the sorptive flotation system."	(Abdulhussein & Alwared, 2019)
Removal of heavy metals from wastewater effluents by biosorptive flotation	"Flotation was subsequently shown to be an effective solid-liquid separation process, avoiding the problem of the separation of fine sponge-like moss flocs from the effluent by conventional filtration. A dispersed air flotation column was applied for the generation of fine bubbles to realise the solid-liquid separation. Biosorptive flotation may have practical applications for the removal of hazardous metals from contaminated water supplies."	(Aldrich & Feng, 2000)
Removal of toxic metal ions from aqueous systems by biosorptive flotation	"Flotation removals, following laboratory-scale experiments, were found to be in the order of 100, 85, and 70% for copper, zinc, and nickel, respectively. In pilot-scale experiments, biomass sorption capacities were determined as 25 for copper, 81 for zinc, and 7 μmol dm^{-3} for nickel. The	(Zouboulis et al., 2002)

	order of biomass affinity regarding the studied metals was Cu > Zn > Ni."	
Comparison study of biosorption and coagulation/air flotation methods for chromium removal from wastewater: experiments and neural network modeling	"For the C/DAFM, poly aluminum chloride (PAC) and FeCl3 were used as coagulants, and the dose was determined by jar test. In optimal conditions of pH 7.5, pressure of 3 bars, and flotation time of 5 min, a maximum of 85% of chromium was extracted. In a comparison of C/DAFM and BM, C/DAFM showed higher ability and greater potential for Cr(VI) removal."	(Esmaeili et al., 2015)
Biosorptive flotation of nickel and aluminum ions from aqueous solution	"The maximum sorption capacity was found to be 7.63 and 41.59 mg g-1 at pH 5.0 for Ni (II) and Al (III), respectively (initial concentration of 50 mgL^{-1}) and temperature 25 °C. Moreover, the ionic strength of the water solution showed a deleterious role in the biosorption process. The recoveries of the loaded biomass with nickel (II) and aluminum (III) by flotation were found to be in the order of 90 and 93%, respectively, at pH around 5. The higher floatability for both species was obtained in a maximum time of 20 minutes."	(Cayllahua & Torem, 2011)
Removal of Copper(II) from Aqueous Solutions by Biosorption-Flotation	"Cu(II) removal efficiency exhibited a maximum of 97.09 % in the following operating conditions: biosorption pH 4.5, Cu(II) initial concentration 250 mg/L, biosorbent dosage 0.5 % w/v, agitation rate 200 rpm, temperature 20 °C, biosorption time 30 min, flotation pH 9, air pressure 4.5 × 105 Pa, dilution ratio 3:1, flotation time 10 min, collector CPB 0.01 M, and molar ratio collector/Cu(II) 5 × 10−1:1."	(Stoica et al., 2015)
Biosorptive flotation for metal ions removal: the influence of surface tension	"Under the optimized experimental conditions, the removal of metals by sorption and the recoveries of biomass by flotation were found to be in the order of 95% (or even more) at pH around 7, whereas the surface tension measurements were lowered and the contact angles were increased in this system, hence improving the biomass floatability."	(Zouboulis & Matis, 2009)
Competitive removal of lead, copper, and cadmium ions by sorptive flotation using marble wastes	"The results indicated that maximum adsorption capacity was 24.695, 19.4675 and 7.91 mg/g dry marble within 90 minutes contact time at pH 5-6 and the maximum removal efficiency obtained by sorptive flotation at relatively short time in single system was about 99.95%, 84.58% and 78.697% for Pb(II), Cu(II) and Cd(II) ions, respectively"	(Alwared & Sadiq, 2019)
Removal of Copper(II) from Some Environmental Samples by Sorptive-Flotation Using Powdered Marble Wastes as Sorbents and Oleic Acid as Surfactant	"Nearly 100 % of PMW and Cu(II) were removed from aqueous solutions at pH 7 after stirring for 10 min and at room temperature (~25°C)."	(Ghazy et al., 2004)
Biosorptive flotation of copper ions from dilute solution using BSA-coated bubbles	"A combination of collector and flocculant at a concentration of 3×10^{-4} M and 0.025 g/l, respectively, led to an increase in copper recovery to nearly 35% at pH 7."	(Nazari et al., 2015)
Removal of heavy metals using waste sludge by biosorptive flotation	"The system attained equilibrium about 20 min. Maximum adsorption capacity of Cu(II) and Cr(II) were 196.08 and 158.73 mg/g, respectively."	(Chang-Han & Kab-Hwan, 2005)

Sorptive flotation combines adsorption with flotation, enhancing performance especially in mixed-ion systems. Materials such as activated carbon, barley husk, and graphene oxide are commonly used as pre-sorbents. Mohammed & Mohammed (2014) reported that integrating barley husk in Pb^{2+} flotation increased efficiency by 10% compared to conventional flotation. In biosorptive systems, biomaterials (e.g., algal biomass, tea saponins, powdered marble waste) act as eco-friendly and cost-effective collectors. Cayllahua & Torem (2011) demonstrated that biomass-assisted flotation achieved 90–93% removal of Ni^{2+} and Al^{3+}. Similarly, Stoica et al. (2015) achieved 97% Cu^{2+} removal using biosorption-flotation under optimized conditions.

Biosorptive flotation is particularly advantageous due to its environmental compatibility, lower operational cost, and reduced chemical usage, although it may require longer contact times and suffer from collector variability.

5. Conclusion

Ion flotation provides a selective, effective, and cost-efficient method for the extraction of heavy metals from dilute wastewater. This review has indicated that traditional ion and precipitate flotation techniques are successful for quick metal removal, while sorptive and biosorptive modifications contribute to sustainability by utilizing eco-friendly materials. Advances such as nanomaterial collectors and biosurfactants have enhanced both performance and environmental compatibility. Despite achieving high removal rates, there are still challenges related to surfactant recovery, sludge management, and the application of these methods on a larger scale. Ongoing research should prioritize process integration, pilot studies, and environmental evaluations to promote practical implementation. Ion flotation, particularly in its hybrid forms, shows significant potential as a sustainable option within contemporary wastewater treatment approaches.

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