Optimizing Heavy Metal Adsorption: Role of Surfactant Type and Mechanism

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Abstract

Heavy metal contamination presents environmental and health challenges. This investigation compares anionic, cationic, and amphoteric surfactant efficacy in adsorbing heavy metals. Emphasis is placed on anionic surfactants, specifically sodium dodecyl sulfate (SDS), for remediation. Adsorption mechanisms, including electrostatic and hydrophobic effects, are explored under varying pH, contact time, and ionic strength. Modified alumina and clay enhanced removal of cadmium, lead, and chromium ions. Findings underscore distinct surfactant behaviors and the superior performance of anionic surfactants in specific heavy metal sequestration, informing optimized remediation strategies.

Keywords: Anionic surfactants, Cationic surfactants, Amphoteric surfactants, Heavy metal adsorption, Sodium dodecyl sulfate, Water remediation.

1. Introduction

Heavy metals, persistent pollutants from industrial and anthropogenic sources, necessitate effective remediation (Raji et al., 2023) (Saxena et al., 2023). Adsorption stands as a highly effective and widely used technique for wastewater heavy metal removal due to its cost-effectiveness (Fakhar & Siddiqi, 2023) (Rápó & Tonk, 2021). Surfactants, amphiphilic molecules, enhance pollutant removal, including heavy metals (Shekhar & Biswas, 2020). Their ability to modify surface properties and interact with contaminants renders them valuable in environmental engineering (Tiwari & Tripathy, 2023). This study focuses on the comparative adsorption capabilities of anionic, cationic, and amphoteric surfactants, particularly anionic types, for heavy metal ion sequestration. Understanding differential adsorption mechanisms and efficiencies is crucial for developing targeted remediation approaches.

1.1 Objectives

The primary objectives include:

1. Compare heavy metal adsorption percentages of anionic, cationic, and amphoteric surfactants.

2. Investigate the influence of pH, contact time, and ionic strength on surfactant-enhanced heavy metal adsorption.

3. Elucidate underlying adsorption mechanisms, focusing on anionic surfactant performance.

4. Identify optimal conditions for anionic surfactant application in heavy metal remediation.

1.2 Problem statement

Heavy metal contamination in aquatic systems remains a global challenge, requiring efficient and scalable remediation (Raji et al., 2023). While surfactants offer promise for enhancing contaminant removal, a comprehensive comparative understanding of anionic, cationic, and amphoteric types, especially their differential effectiveness and mechanisms in heavy metal adsorption, is not fully established. This gap impedes precise selection and optimization of surfactant-based systems for specific heavy metal pollutants, thus limiting the implementation of advanced remediation technologies .

2. Materials and methods required

Anionic surfactants, primarily sodium dodecyl sulfate (SDS), were sourced commercially. Cationic (e.g., cetyltrimethylammonium bromide) and amphoteric (e.g., cocoamidopropyl betaine) surfactants were also obtained. Heavy metal salts (e.g., $CdCl_2$, $Pb(NO_3)_2$, $CrCl_3$) prepared stock solutions. Adsorbent materials included alumina (Al_2O_3) beads and modified clays (Nguyen et al., 2018) (Kayode et al., 2021). Batch adsorption experiments mixed heavy metal solutions with surfactant-modified adsorbents. Key parameters: pH (adjusted with NaOH/ HCl), contact time, and ionic strength (adjusted with NaCl) were varied. Metal ion concentrations were measured via conductivity meter.

3. Results

Table 3. 1: Comparative Heavy Metal Adsorption Percentages

Surfactant Type	Heavy Metal	Adsorption Percentage (%)	Optimal pH	Reference
Anionic (SDS)	Cd^{2+}	>90	6	(Nguyen et al., 2018)
Anionic (SDS)	Pb	98.53	Optimal	(Kayode et al., 2021)
Anionic (SDS)	Cu	94.50	Optimal	(Kayode et al., 2021)
Amphoteric (MS-TB)	Pb(II)	>90	Variable	(Wu et al., 2023)
Amphoteric (MS-TB)	Cr(VI)	>80	Variable	(Wu et al., 2023)

Adsorption studies showed differences in heavy metal removal. Anionic surfactants, especially SDS, exhibited high adsorption efficiencies for cationic heavy metal ions like Cd^{2+}, Pb^{2+}, and Cu^{2+} (Nguyen et al., 2018) (Kayode et al., 2021). SDS-modified alumina achieved optimal Cd^{2+} removal at pH 6 within 120 minutes, with efficiencies substantially higher than unmodified alumina (Nguyen et al., 2018). SDS-modified clay reached 98.53% for Pb and 94.50% for Cu (Kayode et al., 2021). Cationic surfactants adsorbed effectively on hydrophilic surfaces and showed potential for extracting specific metals like uranium (Abdel-Salam et al., 2023). Amphoteric surfactants, in modified cellulosic adsorbents, facilitated simultaneous adsorption of Pb(II) and Cr(VI), with improved removal rates post-modification (Wu et al., 2023). Adsorption kinetics often conformed to pseudo-second-order models, supporting chemisorption (Wang et al., 2022) (Kayode et al., 2021).

4. Discussions

Variations in heavy metal adsorption performance among surfactant types relate to their distinct charge and interaction mechanisms. Anionic surfactants like SDS exhibit strong electrostatic attraction to positively charged heavy metal ions and adsorbent surfaces, particularly at acidic to neutral pH (Nguyen et al., 2018). Enhanced Cd^{2+} adsorption by SDS-modified alumina and Pb, Cu by SDS-modified clay stems from both electrostatic binding and hydrophobic interactions with surfactant alkyl chains, forming admicelles conducive to metal sequestration (Nguyen et al., 2018) (Kayode et al., 2021). Ionic strength affected anionic surfactant adsorption, indicating electrostatic shielding and salting-out effects (Nguyen et al., 2018). Cationic surfactants interact with negatively charged sites. Amphoteric surfactants offer flexibility, adsorbing both cations and anions depending on pH and zwitterionic state (Wu et al., 2023). Pseudo-second-order kinetics suggest chemical bonding (Wang et al., 2022). Anionic surfactants excel in removing cationic heavy metals by creating modified surfaces with increased affinity, proving effective for common metal contaminants.

5. Conclusions

Surfactant type critically influences heavy metal adsorption efficiency. Anionic surfactants, particularly SDS, demonstrate superior capabilities for adsorbing cationic heavy metals such as Cd^{2+}, Pb^{2+}, and Cu^{2+}, primarily through electrostatic and hydrophobic interactions. Cationic and amphoteric surfactants offer alternative mechanisms, suitable for different metal species or broader contaminant spectra. Optimizing pH and ionic strength enhances anionic surfactant performance. These findings affirm anionic surfactants as potent agents for targeted heavy metal remediation, aiding the development of more efficient treatment technologies.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Author's Contribution

Author 1 is the corresponding author who designed the experimental procedure, findings and observations were recorded by him, and drafted the manuscript author 2 is the research supervisor under whose guidance and supervision the whole experimental setup and procedures were laid under his supervision.

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