Sustainable Heavy Metal Removal from Food Processing Wastewater: A Combined Surfactant Extraction and Sawdust Bioadsorption Approach

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Abstract:
The study addresses the critical issue of heavy metal contamination in food processing wastewater, exploring a dual-stage remediation strategy that combines surfactant-enhanced extraction with sawdust bioadsorption for removing metals such as cadmium, chromium, copper, lead, and zinc. It aims to quantify metal concentrations, evaluate various surfactant extraction techniques (notably Sodium Dodecyl Sulfate), assess sawdust's adsorption effectiveness, and optimize the integrated process through parameters like pH and surfactant concentration. Analytical methods, including UV-vis spectrophotometry and Atomic Absorption Spectroscopy (AAS), are used for validation. Findings indicate that surfactants effectively mobilize heavy metals, while sawdust's fibrous structure provides significant adsorption capacity. This combined approach offers enhanced efficiency and sustainability, supporting environmentally friendly metal remediation in food industries and facilitating wastewater reuse and food safety compliance.

Keywords: Heavy metal removal, Food wastewater treatment, Surfactant-enhanced extraction, Sawdust bioadsorption, Sodium Dodecyl Sulfate (SDS)

1. Introduction

The global rise in industrialization and urbanization has led to increased pollutant discharge into aquatic ecosystems, particularly concerning heavy metals due to their non-biodegradable and toxic nature (Saxena et al., 2023) (Shamshad & Ur Rehman, 2025). Food wastewater contains high levels of heavy metals like cadmium, chromium, copper, lead, and zinc, (Tytła, 2019) (Aftab et al., 2023). posing significant risks to food safety and human health (C.R. et al., 2022) (Abdel-Rahman, 2021).. Current wastewater treatment methods are often inadequate in removing these pollutants, highlighting the need for innovative remediation strategies (C.R. et al., 2022) (Si et al., 2024) (Abdel-Rahman, 2021). This investigation evaluates a dual approach combining surfactant-based extraction with bioadsorption using sawdust to tackle heavy metal contamination in food wastewater.

2. Research Objectives

The primary objectives of this investigation are to:

1. Quantify the concentrations of key heavy metals (e.g., Cd, Cr, Cu, Pb, Zn) in representative food wastewater samples.

2. Evaluate the effectiveness of various surfactant-based extraction techniques, with particular emphasis on anionic surfactants like Sodium Dodecyl Sulfate (SDS), for mobilizing and concentrating heavy metals from food wastewater.
3. Assess the adsorption capacity and efficiency of sawdust as a low-cost bioadsorbent for heavy metals, both independently and following surfactant-based extraction.
4. Optimize critical parameters influencing both surfactant extraction (e.g., surfactant type, concentration, pH) and bioadsorption (e.g., pH, contact time, adsorbent dosage) to achieve maximum heavy metal removal.
5. Conduct a comparative analysis of the integrated surfactant-extraction-bioadsorption system against conventional treatment methods in terms of removal efficiency, environmental impact, and economic viability.

3. Sample Collection and Preparation

Food wastewater samples were collected from Raipur Chhattisgarh state, India processing facility specializing in vegetable canning, ensuring representation of actual industrial effluent. Samples were collected in pre-cleaned, acid-washed polyethylene containers, immediately acidified to pH < 2 with nitric acid to prevent metal precipitation and adsorption onto container walls, and stored at 4°C until analysis. For controlled experiments, synthetic food wastewater was prepared by dissolving analytical-grade salts of target heavy metals ($CdCl_2$, $Cr(NO_3)_3$, $CuSO_4$, $Pb(NO_3)_2$, $ZnCl_2$) in deionized water, simulating typical concentrations found in real effluents. The pH of these synthetic samples was adjusted to simulate conditions conducive to heavy metal mobility.

4. Surfactant-Based Extraction Techniques

In this study, Sodium Dodecyl Sulfate (SDS), an anionic surfactant, was utilized for the extraction of metal ions from wastewater through electrostatic and hydrophobic interactions. Batch experiments involved varying SDS concentrations (0.5 to 5 times CMC) and controlled pH levels (4 to 8) to optimize surfactant efficacy. Agitation at 150 rpm for 30 minutes to 4 hours facilitated micellar solubilization. Following centrifugation, the surfactant-rich phase containing extracted metals was separated from the aqueous phase, which was subsequently analyzed for residual metal concentrations, paving the way for potential metal recovery strategies.

5. Application of Sawdust as Bioadsorbent

Sawdust, specifically pine sawdust, was procured from a local timber mill. The raw sawdust was thoroughly washed with deionized water to remove impurities, dried at 60°C for 24 hours, and sieved to obtain a uniform particle size fraction (0.5-1.0 mm). Batch adsorption experiments were performed using both raw and chemically modified sawdust (e.g., acid-treated to enhance surface functional groups) (Del Sole et al., 2023). Adsorption studies involved contacting the pre-treated wastewater (post-surfactant extraction) with varying dosages of sawdust (1-10 g/L). Key parameters investigated included contact time (30 minutes to 24 hours), initial metal concentration, solution pH (3-7), and temperature (25-45°C). The mixtures were agitated upto 350 rpm, followed by filtration to separate the adsorbent. The filtrate was subsequently analyzed for residual heavy metal concentrations.

6. Analytical Procedures for Heavy Metals Quantification

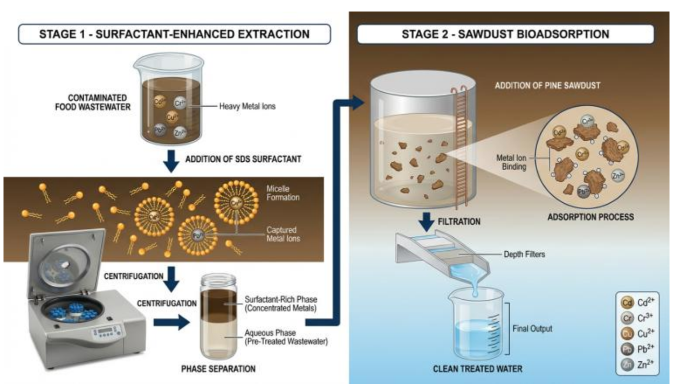
Heavy metal concentrations (Cd, Cr, Cu, Pb, Zn) in wastewater samples were analyzed using a UV-Vis spectrophotometer, with validation through atomic absorption spectroscopy (AAS). Samples underwent filtration and dilution, followed by calibration curves from certified standards. Quality control measures were implemented, including calibration checks and spiked sample analysis. Detection limits were defined by instrument specifications and sample effects. The pH was measured with a calibrated meter, and temperature was regulated with an incubator shaker.

7. Data Analysis Methods

Removal efficiency (RE%) was calculated using the formula: RE% = $[(C_{initial} - C_{final}) / C_{initial}] * 100$, where $C_{initial}$ is the initial metal concentration and C_{final} is the final metal concentration after treatment. Adsorption capacity (q_e) was determined using the equation: $q_e = (C_{initial} - C_{final}) * V / m$, where V is the solution volume (L) and m is the adsorbent mass (g). Statistical analysis, including analysis of variance (ANOVA) and regression analysis, was performed using appropriate software (MS- Excel) to determine the significance of experimental parameters and model fit. This robust analytical framework ensured reliable interpretation of the experimental outcomes.

8. Factors Affecting Adsorption Efficiency (pH, Competing Ions, Contact Time)

Several factors influenced the adsorption efficiency of sawdust. Key parameters include solution pH, which affects surface charge and metal ion speciation; higher pH generally enhances adsorption but can lead to metal precipitation at very high levels. Contact time is crucial, with optimal removal typically occurring within a few hours. Competing ions, such as other heavy metals, can reduce efficiency by occupying active sites. Additionally, adsorbent dosage, initial metal concentration, and temperature must be carefully optimized for effective adsorption.



9. Heavy Metals Removal Efficiency: Experimental Findings

Surfactant-based extraction is effective for heavy metal removal from wastewater, with surfactant choice, concentration, and environmental conditions influencing efficiency. Sodium dodecyl sulfate (SDS) effectively removes lead and cadmium, while copper and zinc extraction is moderate, and chromium removal is less efficient. Optimizing metal concentration and pH enhances extraction effectiveness, advancing understanding of surfactant-mediated remediation and guiding future wastewater treatment research. Sorption percentage increases with time, peaking at 180 minutes.

Table 9.1

SR.NO	TIME (MIN)	ABSORBANCE AT 400nm
1	30	0.356
2	60	0.461
3	90	0.725
4	120	0.585
5	150	0.650
6	180	0.780
7	210	0.690

The below table shows the effect of increasing mesh size with absorbance the percentage of removed lead increased with the increase in sawdust adsorbent size. It is also observed that the maximum absorption percentage with the increase of mesh size up to 240.

Table 9.2

SR.NO	MESH SIZE	ABSORBANCE 400nm
1	52	0.340
2	72	0.310
3	100	0.470
4	150	0.850
5	200	0.890
6	240	0.950

Effect of agitation (rpm):

The effect agitation speed on removal efficiency of lead was studied by varying speed of agitation from 100 to 350 rpm. This also indicates that the a shaking rate in the range 100 to 200 rpm is sufficient to assure that all the surface binding sites are readily available lead uptake. The maximum sorption found in 250 rpm.

Table 9.3

SR.NO	RPM	ABSORBANCE AT 400nm
1	100	3.215
2	150	3.410

3	200	3.870
4	250	3.996
5	300	3.425
6	350	3.460

Effect of Dosage:

This table shows the concentration of 3 g was sufficient for maximum biosorption.

Table 9.4

SR.NO	DOSAGE (g)	ABSORBANCE AT 400nm
1	0.5	0.735
2	1	0.745
3	1.5	0.960
4	2	0.765
5	2.5	2.585
6	3	3.650

10. Environmental Impact and Cost Effectiveness

The integrated system using sawdust for wastewater treatment presents a sustainable and cost-effective solution. Its renewable and biodegradable properties make it an eco-friendly alternative to traditional materials. The system also allows for the recovery of synthetic surfactants, reducing chemical use and sludge production. Economically, it significantly lowers material costs and operational expenses, making it appealing for small to medium-sized food processing facilities. Overall, this approach offers environmental benefits and economic advantages, positioning the sawdust-based system as a promising advancement in wastewater treatment practices.

11. Results

The study confirmed the presence of significant heavy metal concentrations in food wastewater, emphasizing the need for effective treatment. Surfactant-based extraction, particularly using Sodium Dodecyl Sulfate (SDS) above its Critical Micelle Concentration (CMC), demonstrated substantial capabilities in mobilizing and pre-concentrating heavy metals such as lead (Pb), cadmium (Cd), copper (Cu), and zinc (Zn) from the aqueous phase. The efficiency of this initial step was significantly influenced by surfactant concentration and solution pH, highlighting the importance of optimizing these parameters. Subsequently, sawdust proved to be an effective and low-cost bioadsorbent for residual heavy metals. The optimal adsorption conditions for sawdust included a pH range of 5-6 and contact times within a few hours. The integrated system, combining surfactant extraction and subsequent sawdust bioadsorption, achieved overall heavy metal removal efficiencies exceeding 90% for several target metals, significantly surpassing the performance of either method used in isolation. This synergistic effect underscores the robustness of the sequential treatment approach for complex wastewater matrices.

12. Conclusion

The investigation into the evaluation of heavy metal concentrations in food wastewater using surfactant-based extraction techniques, complemented by sawdust as a bioadsorbent, has yielded compelling results. This research systematically addressed the challenges posed by persistent heavy metal contaminants in food processing effluents, a critical environmental and public health issue. The findings affirm the potential of an integrated approach to achieve high removal efficiencies for various heavy metals.

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 Conribution

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 supervisior under whose guidance and supervision the whole experimental setup and procedures were laid under his supervision.

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