Dual-Stage Remediation of Heavy Metals in Food Wastewater: Synergistic Application of Surfactant-Enhanced Extraction and Microemulsion

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Abstract

The water quality of Raipur District, Chhattisgarh, India, was comprehensively assessed through the determination of physicochemical parameters and heavy metal concentrations. The study incorporated the use of sodium dodecyl sulfate (SDS) as a surfactant and microemulsion techniques to enhance the detection and quantification of trace heavy metals. Water samples were collected from various food vending sources within the district (Tamrakar et al., 2022). Parameters such as pH, electrical conductivity, total dissolved solids, alkalinity, and hardness were analyzed alongside lead, cadmium, chromium, and other heavy metals. The water quality was subsequently evaluated using the Water Quality Index (WQI) framework established by Brown et al. (1972). Results indicated varying levels of contamination, particularly concerning heavy metals, which often exceeded permissible limits due to anthropogenic influences (Tamrakar et al., 2022). The application of SDS and microemulsion improved the sensitivity of heavy metal analysis. A comparative assessment with the Brown et al. (1972) WQI provided a robust classification of water suitability, highlighting areas requiring urgent intervention for water resource management.

Keywords: Water quality Index, Microemulsion, Heavy metals, Food wastewater, Surfactants, Uv-vis spectrophotometer

1. Introduction

Assessing water quality is essential for protecting ecological integrity and public health, especially in areas that are rapidly becoming more urbanized and industrialized (Ewaid et al., 2020; Tamrakar et al., 2022). Raipur District, a major urban area in Chhattisgarh, India, is under increasing environmental stress, which could cause its water supplies to deteriorate (Tamrakar et al., 2022). Living things are at serious risk from heavy metals, which are known to be hazardous even at low doses (Lace & Cleary, 2021). Their prevalence in aquatic ecosystems is frequently associated with agricultural runoff and industrial discharges (Mathew & Radhika, 2022). Therefore, sensitive and accurate detection techniques are essential for efficient monitoring. The recovery and detection limits of trace analytes are greatly improved by surfactant-assisted extraction, such as those that use sodium dodecyl sulfate (SDS) and microemulsion methods.

(Jain et al., 2023). Using sophisticated analytical methods, this study describes the physicochemical characteristics and heavy metal content of water samples from Raipur District. These results are then compared to the Water Quality Index (WQI), which was created by Brown et al. (1972) and provides a standardized assessment of overall water quality.

2. Methodology

2.1 Study Area: Raipur District, Chhattisgarh

The sampling area encompassed various surface and groundwater sources within Raipur District, Chhattisgarh, India (Tamrakar et al., 2022) (Sharma, 2013). This region experiences considerable anthropogenic activity, including urbanization and industrial development, which potentially impact local water bodies (Tamrakar et al., 2022). Specific sites were selected to represent a spectrum of influences, from relatively less disturbed areas to those in proximity to sites and potential discharge points.

2.2 Sample Collection and Preparation

Water samples were collected following standard protocols to ensure representativeness and minimize contamination. Polyethylene bottles, pre-cleaned with acid, were used for collection. Samples designated for heavy metal analysis were acidified immediately after collection with nitric acid to a pH below 2, preventing precipitation and adsorption to container walls. All samples were transported to the laboratory under refrigerated conditions and processed promptly for analysis.

3. Determination of Physicochemical Parameters

Standard analytical methods were employed to determine physicochemical parameters. Parameters such as pH, electrical conductivity (EC), and total dissolved solids (TDS) were measured on-site using portable meters. In the laboratory, alkalinity, hardness, chlorides, sulfates, and nitrates were quantified using titrimetric and spectrophotometric techniques according to established environmental standards. These parameters provide a baseline understanding of general water characteristics (Kerketta et al., 2013).

4. Heavy Metals Analysis

Heavy metal concentrations (e.g., Pb, Cd, Cr, Ni, Fe, As) were determined using Uv-vis Spectrophotometer and for data validation Atomic Absorption Spectroscopy (AAS) (Ghosh et al., 2023). Prior to analysis, samples underwent appropriate digestion procedures to convert metals into a soluble form suitable for instrumental detection. Quality control measures, including calibration standards and spiked samples, were maintained throughout the analytical process.

5. Use of SDS as Surfactant and Microemulsion Technique

To enhance the sensitivity and recovery of heavy metals, a surfactant-assisted dispersive liquid-liquid microextraction (SA-DLLME) method was applied (Jain et al., 2023). Sodium dodecyl sulfate (SDS) was used as the anionic surfactant, forming microemulsions that effectively extract target heavy metal ions from the aqueous phase into a smaller organic phase (Li et al., 2022). This pre-concentration step significantly lowered detection limits, enabling the quantification of trace metal concentrations that might otherwise fall below instrument capabilities. The efficiency of extraction was optimized by varying SDS concentration, pH, and solvent type.

6. Calculation of Water Quality Index (Brown et al., 1972)

The Water Quality Index (WQI) model proposed by Brown et al. (1972) was utilized to provide a single, comprehensive numerical score for water quality. This method involves assigning weights to individual parameters based on their relative importance in water quality assessment. Sub-indices are calculated for each parameter, which are then aggregated to yield the overall WQI. This index facilitates classification of water samples into categories reflecting their suitability for various uses (Ewaid et al., 2020).

7. Results

7.1 Physicochemical Parameters of Water Samples

Analysis of physicochemical parameters revealed notable variations across the sampled locations within Raipur District. pH values generally ranged from slightly acidic to neutral, with a few sites exhibiting alkalinity. Electrical conductivity and total dissolved solids often reflected the influence of urban runoff and dissolved salts. Alkalinity and hardness levels indicated varying geological influences and anthropogenic inputs. For instance, several food wastewater showed elevated nutrient levels, indicative of surface runoff and solid waste disposal (Tamrakar et al., 2022).

7.2 Concentration of Heavy Metals

Heavy metal analysis demonstrated the presence of several metals, including lead (Pb), cadmium (Cd), chromium (Cr), and nickel (Ni), in varying concentrations. While some metals were within permissible limits, others, particularly at sites influenced by food manufacturing industries, exceeded recommended standards for drinking water (Ramal et al., 2021). For example, studies in similar regions identified elevated levels of Pb, Cr, and Ni, often linked to industrial and anthropogenic activities (Soren et al., 2023).

7.3 Impact of SDS and Microemulsion on Detection Sensitivity

The application of SDS as a surfactant and the microemulsion technique significantly improved the analytical sensitivity for heavy metals. This method allowed for the detection of lower concentrations of metals than conventional direct analysis. Enhanced extraction efficiency led to more accurate quantification of trace elements, which is crucial for assessing potential health risks associated with chronic low-level exposure (Lace & Cleary, 2021). The pre-concentration step reduced matrix interferences, yielding cleaner signals and improved precision.

7.4 Comparison with Brown et al. (1972) Water Quality Index

Water samples were clearly categorized using the Water Quality Index (WQI), which was computed using the Brown et al. (1972) framework. Due to lower WQI ratings, a number of locations—especially food vending sites—were deemed inappropriate for direct consumption or in need of major treatment (Tamrakar et al., 2022). On the other hand, other samples showed good to exceptional water quality, which was consistent with the index's previous classifications (Al-Omran et al., 2015). This comparison brought to light the district-wide differences in the effects of environmental stressors and the localized character of pollution. Brown et al. (1972) used the model to determine the water samples' WQI.

The formula used: $Wn = K/Sn$ … *(7.4i)*

$$qn = \frac{100\ [\mathrm{Vn-V0}]}{[\mathrm{Sn-V0}]}$$ … *(7.4ii)*

Overall WQI = $\sum WnQn / \sum Wn$ … *(7.4iii)*

Wn = K/ Sn, where

Wn = unit weight for the n^{th} parameters, Sn = Standard value for n^{th} parameters

K = Constant for proportionality.

q_n = Quality rating for the n^{th} water quality parameter V_n=Estimated value of the n^{th} parameter at a given sampling station, Sn =Standard permissible value of the n^{th} parameter, V_o = Ideal value of an n^{th} parameter in pure water. (i.e., 0 for all other parameters except the parameter pH and Dissolved oxygen (7.0 and 14.6 mg/L respectively), Unit weight was calculated by a value inversely proportional to the recommended standard value Sn of the corresponding parameter.

Table 7.1 Classification of water quality based on weighted arithmetic WQI method

Wqi	**Status**
0 – 25	Excellent
26 – 50	Good
51 – 75	Poor
76 – 100	Very Poor
Above 100	Unsuitable for drinking

Table 7.2 Microemulsion formation

ME	**W0**	**Surfactant**			**N- butanol %**	**N-hexanol %**
		SDS	**CTAB**	**TRITON X-100**		
1	5	21	18.9	13.3	4	1
2	5.5	20	17.9	12.7	4	1
3	6	19	15.9	12.5	4	1
4	6.5	2	15.9	11.6	4	1
5	7	17	14.9	11	4	1
6	7.5	16	12.9	10.7	4	1
7	8	15	11.9	10.3	4	1
8	8.5	14	11.9	9.9	4	1

Table 7.3 Summary of Average Physicochemical Parameters and Heavy Metal Concentrations across Selected Sites (Mean ± SD).

PARAMETER	**SITE A**	**SITE B**	**SITE C**	**BIS 2012) LIMIT**
pH	7.2 ± 0.3	6.8 ± 0.2	7.5 ± 0.4	6.5- 8.5
EC (µS/cm)	450 ± 25	680 ± 40	310 ± 15	<2000
TDS (mg/L)	290 ± 15	440 ± 20	200 ± 10	<500
Pb (mg/L)	0.008 ±0.001	0.015 ±0.002	0.004 ±0.001	<0.01
Cd (mg/L)	0.002 ± 0.0005	0.006 ± 0.001	0.001 ±0.0002	<0.003

8. Discussions

8.1 Implications of Physicochemical and Heavy Metal Results

The physicochemical characterization revealed substantial heterogeneity in water quality within Raipur District. Elevated levels of parameters such as EC and TDS in certain areas typically reflect increased dissolved mineral content and anthropogenic inputs. The presence of heavy metals, including Pb and Cd, exceeding prescribed limits in some samples, underscores a potential environmental and public health concern (Ramal et al., 2021). These metals often originate from industrial discharge, agricultural runoff, and inadequate waste management, consistent with observations in rapidly urbanizing regions (Mathew & Radhika, 2022) (Tamrakar et al., 2022). The varying concentrations suggest localized pollution sources, necessitating targeted management strategies.

8.2 Effectiveness of SDS and Microemulsion Techniques

The integration of SDS as a surfactant and microemulsion techniques proved highly effective in enhancing the analytical capabilities for heavy metals. This approach significantly improved the sensitivity and lowered the detection limits of instrumental analysis. The microemulsion-based pre-concentration allowed for the accurate quantification of trace heavy metals that might otherwise be overlooked, providing a more complete picture of contamination profiles. This highlights the utility of such advanced sample preparation methods for robust environmental monitoring, particularly for pollutants present at very low, yet potentially harmful, concentrations (Jain et al., 2023).

8.3 Comparative Assessment Using Water Quality Index

The application of the Water Quality Index (WQI) developed by Brown et al. (1972) provided a valuable framework for interpreting the complex analytical data. By consolidating multiple parameters into a single score, the WQI enabled a straightforward classification of water quality across the sampled sites. This facilitated direct comparison of water suitability for various uses and identified specific areas where water quality was compromised. The WQI effectively categorized water bodies, indicating that certain urban ponds require urgent remedial actions to restore their quality and prevent further degradation (Tamrakar et al., 2022). This approach offers a clear metric for stakeholders and policymakers.

9. Conclusions

This investigation into the water quality of Raipur District, Chhattisgarh, using physicochemical analysis, heavy metal determination with SDS-assisted microemulsion, and Brown et al. (1972) Water Quality Index, provides critical insights into the state of local water resources. Elevated heavy metal concentrations and unfavorable physicochemical parameters in specific locations underscore the pervasive impact of anthropogenic activities. The enhanced sensitivity achieved through SDS and microemulsion techniques demonstrated their value for accurate trace metal quantification. The WQI framework proved instrumental in classifying water quality, pinpointing areas of concern that demand immediate attention for effective water resource management and pollution control. Sustained monitoring and targeted interventions are essential to safeguard these vital water sources.

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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