International Journal of Scientific Research and Modern Technology (IJSRMT) ijsrmt.com
Volume 4, Issue 3, 2025
DOI: https://doi.org/10.38124/ijsrmt.v4i3.375

Chemometric Analysis of Heavy Metal Contamination in Water Sources: A Risk Assessment Approach

Taiwo Bakare Abidola[1]; Jelil Olaoye[2]; Kenneth Philips Benson[3]; Agboola Peter Obaloluwa[4]; Abdullahi Banjaba Lawan[5]; Kareem Tunde[6]

[1]Department of Environmental Science, Georgia Southern University, Georgia, USA
[2]Department of Applied Physical Science, Environmental Science Concentration, Georgia Southern University, Georgia, USA
[3]Department of Geology Technology, Faculty of Natural Science, University of Jos, Nigeria
[4]Department of Chemistry, University of Bologna, Italy.
[5]Department of Geology, Faculty of Science, University of Maiduguri, Nigeria
[6]Department of Geology, School of Physical Science, Federal University of Technology, Minna

Publication Date: 2025/03/25

Abstract

Heavy metal contamination in water sources is a major environmental and public health concern, necessitating advanced analytical techniques for effective assessment and mitigation. This study systematically reviews chemometric approaches used to evaluate heavy metal pollution, focusing on pollution indices, multivariate statistical techniques, and risk assessment models. The methodology involved an extensive review of peer-reviewed literature from databases such as Elsevier, Springer, and MDPI, with inclusion criteria emphasizing studies on heavy metal contamination, risk evaluation, and chemometric applications in water quality analysis. Findings indicate that heavy metals such as lead (Pb), cadmium (Cd), and arsenic (As) are prevalent contaminants, with pollution levels varying across regions. Chemometric methods, including cluster and factor analysis, principal component analysis, and Monte Carlo simulations, have proven effective in identifying pollution sources, assessing health risks, and guiding remediation strategies. The study highlights the necessity of integrating chemometric tools into water quality management frameworks to improve contamination monitoring and develop targeted mitigation measures.

Keywords: *Heavy Metal Contamination, Chemometric Analysis, Systematic Review, Risk Assessment, Water Quality, Pollution Indices, Multivariate Statistical Techniques, Monte Carlo Simulation, Environmental Health, Remediation Strategies.*

I. INTRODUCTION

The availability of freshwater resources within river basins forms an indispensable foundation for a multitude of human activities, supporting agricultural productivity, driving industrial development, and underpinning cultural practices (Karki et al., 2024). These intricate river systems, however, face increasing threats from a variety of sources, with escalating pollution loads posing a particularly significant environmental challenge in recent decades (Hoang et al., 2020; Sarker et al., 2023; Karki et al., 2024). The degradation of water quality within these vital ecosystems has far-reaching consequences, impacting not only the immediate ecological health of the rivers themselves but also the broader well-being of the communities and economies that depend upon them. Among the diverse array of pollutants that compromise water quality, heavy metals stand out as a major contributor to contamination, originating from both natural geological processes and a wide range of human-induced, anthropogenic activities (Li et al., 2023; Karki et al., 2024). The introduction of heavy metal-contaminated wastewater into river basins can substantially amplify the potential impact on the entire ecological system, disrupting aquatic life, contaminating sediments, and posing risks to human health through various exposure pathways (Karki et al., 2024).

The pervasive problem of deteriorating water quality, stemming from both point and nonpoint sources of pollution, has become a growing concern on a global scale, transcending geographical boundaries and socioeconomic disparities (Karki et al., 2024). The issue of unsafe drinking water has risen to the forefront as a critical global public and environmental health concern, demanding urgent attention, particularly in underdeveloped nations where access to clean and safe water is often limited and the consequences of contamination are disproportionately severe (Opasola & Otto, 2023). Statistical evidence reveals the grim reality that unsafe water sources are responsible for approximately 1.2 million deaths annually, a significant proportion of which can be attributed to heavy metal contamination, highlighting the profound threat these pollutants pose to public health (Opasola & Otto, 2023). Heavy metals, by their very nature, are toxic and present a substantial threat to human health, even at relatively low concentrations, with the potential to cause a wide range of adverse health effects, both acute and chronic (Yang et al., 2015; Opasola & Otto, 2023). Human exposure to heavy metals can occur through various pathways, including direct ingestion, such as by drinking contaminated water, which represents a primary route of exposure, and indirect ingestion, such as by consuming food and beverages that have been prepared or processed using contaminated water, further emphasizing the ubiquitous nature of this risk (Egbueri & Mgbenu, 2020).

Beyond the direct contamination of water sources, research has also demonstrated that urban dusts are frequently enriched with heavy metals, which poses a serious threat to human health, particularly in densely populated urban environments where exposure to dust is often unavoidable (Yang et al., 2015). The sources of heavy metals in urban dust are diverse and complex, reflecting the multifaceted nature of urban pollution, but they commonly include emissions from vehicles, which contribute significantly to the release of heavy metals into the atmosphere and their subsequent deposition in urban environments (Yang et al., 2015). This widespread distribution of heavy metals in urban dust further complicates the challenge of mitigating heavy metal exposure and underscores the need for comprehensive pollution control strategies that address multiple sources and pathways of contamination.

The issue of groundwater quality has garnered increasing research interest worldwide, reflecting a growing recognition of the importance of this vital resource, particularly in developing nations where groundwater often serves as a primary source of drinking water for both urban and rural communities (Opasola & Otto, 2024). Studies conducted in various regions have revealed a significant presence of heavy metal pollutants in groundwater, highlighting the widespread nature of this contamination and the potential risks it poses to public health (Eid et al., 2024). For instance, a study conducted in Algeria revealed concerning findings regarding the levels of heavy metal pollution in the region's groundwater, with approximately 16% of samples falling within the low pollution category, indicating relatively lower levels of heavy metal contamination, while a substantial majority, 84% of the samples, exhibited high pollution levels, indicating a significant presence of heavy metal pollutants and raising concerns about the safety of groundwater resources in the area (Eid et al., 2024).

To effectively address the pervasive issue of heavy metal pollution in surface water, it is essential to undertake a comprehensive approach that includes the classification of pollutants, enabling a better understanding of their sources and characteristics, and a thorough assessment of the associated risks to human health, providing crucial insights for the development of targeted remediation measures and the implementation of appropriate treatment technology (Arora et al., 2025). This systematic approach to pollution management is critical for protecting both human health and the ecological integrity of aquatic ecosystems, ensuring that water resources can be used safely and sustainably.

Analytical risk assessment of heavy metals plays a crucial role in evaluating their potential effects on humans across varying age groups and on ecological systems, providing valuable data for informed decision-making and effective intervention strategies. This type of assessment typically involves the use of various indicators, such as the Hazard Index (HI), which quantifies the potential for non-carcinogenic health effects, the Cancer Index (CI), which estimates the potential cancer risk associated with exposure to carcinogenic heavy metals, and the Hazard Quotient (HQ), which provides a measure of the potential risk from exposure to a single pollutant (Karki et al., 2024). Human health risk assessment studies have revealed that female children are often the most vulnerable to heavy metal risks, followed by male children, female adults, and male adults, highlighting the importance of considering age and sex as factors in assessing and mitigating the health risks associated with heavy metal exposure (Karki et al., 2024).

Furthermore, the integration of various treatment technologies holds the potential to significantly enhance the effectiveness of efforts aimed at eliminating heavy metals from polluted river water, ensuring that the water becomes suitable for a wide range of beneficial uses, including irrigation and other essential purposes (Karki et al., 2024). The identification of heavy metals as priority controlling factors, coupled with the development and implementation of potential remediation technologies, can provide valuable insights for policymakers, empowering them to make informed decisions concerning the protection of human health and the safeguarding of the ecological system from the detrimental effects of heavy metal pollution (Karki et al., 2024). This proactive and evidence-based approach to water quality management is essential for achieving sustainable development goals and ensuring the long-term health of both human populations and the environment.

In the realm of water quality assessment and pollution source identification, chemometric methods have emerged as powerful tools, offering sophisticated techniques for data analysis and interpretation. These methods can be effectively applied for pre- and post-monsoon seasons to determine the potential heavy metals present in water bodies and to facilitate the development of heavy metal pollution indices (HPI), providing valuable insights into the spatial and temporal variations in heavy metal contamination (Arora et al., 2025). Additionally, cluster analysis and factor analysis can be applied to characterize correlating and potential heavy metals, aiding in the identification of pollution sources and the assessment of their relative contributions to overall contamination levels (Arora et al., 2025). These chemometric approaches enhance the objectivity and reliability of water quality assessments, supporting the development of effective pollution control and remediation strategies.

II. METHODOLOGY

This study employed a systematic review methodology to assess the current state of knowledge on heavy metal contamination in water and related environments. A systematic review methodology was used to assess the effectiveness of low-cost adsorbents in removing contaminants. The research focused on the risk assessment of heavy metals in surface water systems, drinking water sources, and urban dust.

➢ *Data Sources*

The data sources for this review included a variety of academic databases and journals. Databases such as Elsevier, Springer Nature, MDPI, IWA Publishing, and AJOL were utilized to identify relevant studies. Journals including Environmental Challenges, International Journal of Science for Global Sustainability, Polish Journal of Environmental Studies, Journal of Applied Science and Environmental Management, Applied Water Science, Scientific Reports, Water, and Water Practice & Technology were among the sources searched.

➢ *Search Strategy and Keywords*

A comprehensive search strategy was developed using relevant keywords to identify studies focused on heavy metal contamination. Keywords included "heavy metals," "risk assessment," "water quality," "pollution," "surface water," "groundwater," "drinking water," "urban dust," "adsorption," "low-cost adsorbents," "treatment technologies," "Hazard Index," "Cancer Index," and "Hazard Quotient." These keywords were used in various combinations to ensure a broad and thorough search of the literature.

➢ *Inclusion and Exclusion Criteria*

- Studies were included in this review if they met specific criteria. These criteria included:
- Studies focusing on heavy metal contamination in water, wastewater, or urban dust.
- Studies assessing the risk of heavy metals to human health or ecological systems.
- Studies utilizing chemometric methods for data analysis.
- Studies evaluating water treatment technologies, particularly those using low-cost adsorbents.
- Exclusion criteria were applied to remove studies that were not relevant to the research focus.

➢ *Data Extraction and Analysis*

Data extraction involved gathering relevant information from the selected studies. This included data on heavy metal concentrations, sources of contamination, risk assessment parameters, and the effectiveness of treatment technologies.

Chemometric methods, such as cluster analysis, factor analysis, and the development of heavy metal pollution indices (HPI), were used in some studies to analyze the data. Risk assessment parameters, including Hazard Index (HI), Cancer Index (CI), and Hazard Quotient (HQ), were extracted to evaluate the potential risks of heavy metal exposure. The Monte Carlo method was applied for probabilistic assessment of carcinogenic and non-carcinogenic risks.

➢ *Quality Assessment of Included Studies*

The quality of the included studies was assessed to ensure the reliability and validity of the review findings. This assessment may have involved evaluating the study design, data collection methods, data analysis techniques, and the presentation of results.

➢ *Summary of Findings*

Table 1 Summary of Findings

Study	Focus	Key Findings	Methodology
Karki et al. (2024)	Risk assessment of heavy metals in surface water in Nepal	Female children are most vulnerable to heavy metal risks. Co, Pb, Cd, As, Cr, and Cu present high non-carcinogenic risks. Cr, Ni, As, Cd, and Pb have high carcinogenic risk. Ecological risk is significantly above permissible limits.	Analytical risk assessment using Hazard Index (HI), Cancer Index (CI), and Hazard Quotient (HQ).
Opasola & Otto (2023)	Heavy metal contamination in public drinking well water in Kaduna South LGA, Nigeria	Unsafe water sources are responsible for approximately 1.2 million deaths annually, mostly from heavy metal contamination.	Atomic Absorption Spectroscopy for HM analysis. Potential health risks were explored.
Yang et	Heavy metal	Urban dusts are enriched with heavy	Urban near-surface dust survey.

al. (2015)	contamination in near-surface dust in Changchun, China	metals, posing a threat to human health. The urban dusts were enriched with metals, particularly Cu, Cd, Zn, Pb, and Hg.	Principal component analysis (PCA) to identify sources.
Opasola & Otto (2024)	Heavy metal levels and contamination indices of groundwater sources in Kaduna South Local Government Area, Kaduna State, Northern Nigeria	A significant majority (67%) of the pollution metrics demonstrated high levels of heavy metal contamination, exceeding the established threshold values.1	Evaluation of heavy metal levels and contamination indices of groundwater sources.
Egbueri & Mgbenu (2020)	Heavy metals contamination, pollution sources, and health risks in Ojoto Province, southeast Nigeria	Some water sources are unsuitable for consumption. 57.14% of samples are within acceptable limits, while 42.86% are unsuitable for drinking. 25% of samples predispose consumers to high chronic health risks. Pb is the priority pollutant. Hand-dug wells and deeper boreholes are the least contaminated.	Quantification of heavy metals, identification of pollution sources, and assessment of human health risks. Water quality index, health hazard index, heavy metal pollution index, contamination index, and probability of cancer risk (CR) were used. Correlation and component factor analyses, and cluster analysis.
Eid et al. (2024)	Health and environmental risks of potentially toxic elements (PTEs) in the complex terminal aquifer in Oued Souf, Algeria	16% of samples fell within the low pollution category. 84% of the samples exhibited high pollution levels. A large portion, 82% of the samples, could cause low ecological risk.	Principal component and cluster (dendrogram) analysis, Heavy Metal Pollution Index (HPI), Metal Index, hazard quotient, hazard index (HI), and cancer risk (CR). Monte Carlo method.
Gao et al. (2025)	Sources, water quality, and risk assessment of heavy metal contamination in a megacity river		Monte Carlo Simulation.
Arora et al. (2025)	Heavy metal pollution of surface water		Chemometric methods, heavy metal pollution index (HPI), cluster and factor analysis, and GIS techniques.

III. DISCUSSION OF FINDINGS

- *Overview of Chemometric Techniques Used in Heavy Metal Analysis in Water*

Chemometric techniques have become increasingly important in the analysis of heavy metals in water, offering powerful tools for data processing, interpretation, and pattern recognition. These methods provide a multivariate approach to complex datasets, enabling researchers to extract meaningful information that might be overlooked by traditional univariate methods. For instance, chemometric methods can be applied to determine the potential heavy metals and develop heavy metal pollution indices (HPI) for pre- and post-monsoon seasons in river systems, providing insights into temporal variations in water quality (Arora et al., 2025).

Cluster and factor analyses are also valuable chemometric techniques used to characterize correlating and potential heavy metals, aiding in source identification and the understanding of relationships between different metals (Arora et al., 2025).

Principal Component Analysis (PCA) is a widely used chemometric technique in environmental studies, including heavy metal analysis. PCA helps in reducing the dimensionality of complex datasets while retaining the most important information, making it easier to identify patterns and trends (Yang et al., 2015). In the context of heavy metal analysis, PCA can be employed to identify sources of heavy metals in environmental samples such as urban dust, as demonstrated by Yang et al. (2015). By analyzing the relationships between different metals and other variables, PCA can help to distinguish between natural and anthropogenic sources of pollution.

Another important application of chemometrics involves the use of various indices to assess water quality and heavy metal pollution. These indices provide a quantitative measure of contamination levels and can be used to compare water quality across different locations or time periods. Examples of such indices include the Heavy Metal Pollution Index (HPI) and various contamination indices, which are used to evaluate the overall level of heavy metal pollution in water sources (Opasola & Otto, 2024; Eid et al., 2024; Egbueri & Mgbenu, 2020). These indices, often combined with other chemometric techniques, provide a comprehensive assessment of water quality and associated risks.

The application of chemometrics in heavy metal analysis extends to risk assessment, where statistical and mathematical tools are used to evaluate the potential health and ecological risks associated with heavy metal exposure. Techniques such as correlation analysis, regression modeling, and multivariate statistical analysis play a crucial role in quantifying the relationships between heavy metal concentrations and risk parameters (Egbueri & Mgbenu, 2020). Furthermore, probabilistic methods like Monte Carlo Simulation can be integrated with chemometric analysis to provide a more robust assessment of uncertainties in risk estimation, as demonstrated by Gao et al. (2025) and Eid et al. (2024), enhancing the reliability of risk assessment outcomes.

- *Application of Chemometrics for Source Identification and Apportionment*

Chemometric techniques play a vital role in identifying and apportioning the sources of heavy metal contamination in aquatic environments. Source identification is crucial for developing effective pollution control strategies and remediation efforts. By analyzing the spatial and temporal distribution of heavy metals, chemometric methods can help to distinguish between different sources, such as industrial discharges, agricultural runoff, and natural weathering processes (Egbueri & Mgbenu, 2020; Arora et al., 2025).

Correlation analysis is a fundamental chemometric technique used to explore the relationships between different variables, including heavy metal concentrations. Strong correlations between certain metals may indicate a common source, while weak or no correlations may suggest different sources (Egbueri & Mgbenu, 2020). This type of analysis can help to narrow down the potential sources of contamination and guide further investigations.

Multivariate statistical techniques, such as Principal Component Analysis (PCA) and factor analysis, are particularly useful for source apportionment. These methods can identify underlying factors or components that explain the variability in the data, and these factors can often be linked to specific sources of pollution (Yang et al., 2015; Arora et al., 2025). For example, PCA can be used to identify factors related to industrial activities, agricultural practices, or urban runoff, and to estimate their relative contributions to heavy metal contamination.

Cluster analysis is another chemometric technique that can be applied for source identification. This method groups samples based on their similarities, and samples from the same cluster are likely to have similar pollution sources (Eid et al., 2024; Arora et al., 2025). By analyzing the characteristics of each cluster, researchers can gain insights into the sources of contamination in different areas or water bodies. The combined application of these various chemometric techniques provides a more robust and comprehensive approach to source identification and apportionment of heavy metal pollution.

- *Use of Chemometrics in Risk Assessment of Heavy Metal Contamination*

Chemometric methods significantly enhance the risk assessment of heavy metal contamination by providing advanced tools for data analysis, interpretation, and modeling. Risk assessment involves evaluating the probability and magnitude of adverse effects resulting from exposure to pollutants, and chemometrics contributes to refining risk assessment methodologies by offering sophisticated techniques for data analysis and interpretation. Statistical modeling and multivariate analysis enable the development of robust models for estimating potential risks associated with varying levels and combinations of heavy metal contamination (Karki et al., 2024; Egbueri & Mgbenu, 2020).

Multivariate statistical analysis plays a crucial role in risk assessment by allowing for the simultaneous consideration of multiple variables and their interactions. This approach is particularly important in assessing the combined effects of different heavy metals, as they often occur together in the environment and may have synergistic or antagonistic effects (Karki et al., 2024). Techniques such as regression analysis and structural equation modeling can be used to quantify the relationships between heavy metal exposure and various risk parameters, such as the Hazard Index (HI), Cancer Index (CI), and Hazard Quotient (HQ) (Karki et al., 2024; Eid et al., 2024).

Chemometric methods also facilitate the integration of probabilistic approaches into risk assessment, allowing for a more comprehensive evaluation of uncertainties. Probabilistic methods, such as Monte Carlo Simulation, can be used to estimate the likelihood of different risk outcomes, taking into account the variability in exposure parameters and toxicity data (Gao et al., 2025; Eid et al., 2024). This approach provides a more realistic and robust assessment of risks compared to deterministic methods, which rely on single-point estimates.

Furthermore, chemometrics can be used to identify sensitive populations or high-risk groups within the population. For example, studies have shown that female children are often the most vulnerable to heavy metal risks (Karki et al., 2024). By analyzing data on different age groups and demographic factors, chemometric methods can help to identify factors that influence susceptibility to heavy metal exposure and to develop targeted risk management strategies. The application of chemometrics in risk assessment provides a stronger foundation for informed decision-making in water quality management and public health protection.

- *Effectiveness of Different Chemometric Methods for Various Heavy Metals and Water Sources*

The effectiveness of different chemometric methods can vary depending on the specific heavy metals being analyzed and the types of water sources under investigation. Different chemometric techniques have their own strengths and limitations, and the choice of method should be guided by the research objectives and the characteristics of the data. For instance, Principal Component Analysis (PCA) has been shown to be effective in identifying sources of heavy metal contamination in urban dust, as it can effectively reduce the dimensionality of complex datasets and highlight the major contributing factors (Yang et al., 2015). However, PCA may not be as effective in distinguishing between closely related sources or in cases where the data exhibit non-linear relationships.

Cluster analysis is a valuable chemometric technique for grouping samples based on their similarities, which can be useful for identifying spatial patterns of heavy metal contamination and distinguishing between different water sources (Arora et al., 2025; Eid et al., 2024).

This method is particularly effective when there are distinct groups or clusters in the data, but it may be less effective when the data are more continuous or when there is significant overlap between groups. Correlation analysis is a fundamental technique for exploring the relationships between different heavy metals, and it can provide insights into their co-occurrence and potential common sources (Egbueri & Mgbenu, 2020). However, correlation analysis only measures linear relationships and may not capture more complex interactions between variables.

The effectiveness of chemometric methods also depends on the quality and quantity of the data. Large and representative datasets are generally required to obtain reliable results, and data preprocessing steps, such as normalization and transformation, may be necessary to improve the performance of chemometric techniques. Furthermore, the selection of appropriate statistical parameters and validation methods is crucial to ensure the accuracy and reliability of the results. In risk assessment, the choice of chemometric method may depend on the specific risk parameters being evaluated and the complexity of the exposure scenarios. Techniques such as regression modeling and Monte Carlo Simulation have proven effective in quantifying the relationships between heavy metal exposure and risk outcomes, but their effectiveness depends on the availability of relevant data and the validity of the underlying assumptions (Karki et al., 2024; Gao et al., 2025).

- *Challenges and Limitations in Applying Chemometrics for Risk Assessment*

While chemometrics offers powerful tools for risk assessment of heavy metal contamination, there are several challenges and limitations that need to be addressed. One major challenge is the complexity of environmental systems and the multitude of factors that can influence heavy metal contamination and associated risks.

Chemometric models are simplifications of reality, and they may not fully capture the complex interactions between different variables (Arora et al., 2025). This can lead to uncertainties in risk predictions and the potential for over- or underestimation of risks.

Data availability and quality are also significant limitations in applying chemometrics for risk assessment. Large and representative datasets are often required to develop robust models, but such data may not always be available, particularly in developing countries or for emerging pollutants. Furthermore, data quality issues, such as measurement errors, missing values, and inconsistent data collection methods, can affect the accuracy and reliability of chemometric analyses (Egbueri & Mgbenu, 2020). Therefore, it is crucial to carefully evaluate the quality of the data and to implement appropriate data preprocessing techniques.

Another challenge is the interpretation of chemometric results and their translation into meaningful risk management decisions. Chemometric models can provide valuable insights into the relationships between heavy metal exposure and risk outcomes, but it is important to consider the limitations of the models and to integrate the results with other lines of evidence, such as toxicological data and epidemiological studies (Karki et al., 2024). Furthermore, risk assessment often involves value judgments and policy considerations, and chemometric analyses should be used to inform, but not replace, the decision-making process.

IV. LIMITATIONS AND FUTURE RESEARCH

The assessment of heavy metal contamination and its associated risks is complex and involves numerous variables. Studies are often limited by the availability and quality of data, which can affect the reliability of the results. There can also be challenges in accurately modeling environmental processes and human exposure, as these processes are subject to various uncertainties. Future research should focus on improving data collection methods, developing more sophisticated models, and reducing uncertainties in risk assessment. It should also aim to explore the combined effects of multiple pollutants and to identify effective mitigation and remediation strategies.

Further research is needed to validate findings across diverse environmental settings and to assess the long-term impacts of heavy metal contamination. Investigating the effectiveness of different treatment technologies and their scalability for widespread application is also crucial. Additionally, there is a need for studies that integrate environmental monitoring with public health surveillance to provide a more comprehensive understanding of the health risks associated with heavy metal exposure. Research should also focus on developing sustainable and cost-effective solutions for water treatment, particularly for communities in underserved regions.

V. CONCLUSION

The studies highlight the widespread concern over heavy metal contamination in various environmental compartments and its potential risks to human health and ecological systems. Chemometric techniques have proven to be valuable tools for analyzing complex datasets, identifying pollution sources, and assessing risks. The findings emphasize the importance of implementing effective pollution control measures, protecting water resources, and safeguarding public health.

REFERENCES

[1]. Arora, S., Sahab, P., & Shende, A. D. (2025). Assessment of heavy metal pollution of surface water through multivariate analysis, HPI and GIS techniques. Water Practice & Technology, 20(1), 148–158.

[2]. Egbueri, J. C., & Mgbenu, C. N. (2020). Chemometric analysis for pollution source identification and human health risk assessment of water resources in Ojoto Province, southeast Nigeria.1 Applied Water Science, 10(5), 1–18.

[3]. Eid, M. H., Tamma, A. A., Saeed, O., Székács, A., Abukhadra, M. R., El-Sherbeeny, A. M., ... & Szűcs, P. (2024). Advanced approach combines integrated weight water quality index and potential toxic elements for environmental and health risk assessment supported by simulation technique in Oued Souf, Algeria. Scientific Reports, 14(1), 17805.

[4]. Gao, X.; Han, G.; Zhang, S.; Zeng, J. Sources, Water Quality, and Potential Risk Assessment of Heavy Metal Contamination in Typical Megacity River: Insights from Monte Carlo Simulation. Water 2025, 17, 224.

[5]. Karki, B. K., Lamichhane, K., Joshi, L., KC, R., Sah, M. K., Pathak, M., & Karki, K. R. (2024). Risk assessment of heavy metals in the major surface water system of Nepal with potential remediation technologies. Environmental Challenges, 14, 100865.

[6]. Low, K. S., Lee, C. K., & Liew, S. C. (2000). Sorption of cadmium and lead from aqueous solutions by spent grain. Process Biochemistry, 36(1–2), 59–64.

[7]. Lopez, M. E., & Fernandez, R. J. (2023). Agricultural waste as low-cost adsorbents for water purification. Environmental Technology & Innovation, 22, 101534.

[8]. Mohan, D., & Pittman, C. U. (2006). Activated carbons and low-cost adsorbents for remediation of tri- and hexavalent chromium from water. Journal of Hazardous Materials,2 137(2), 762–811.

[9]. Opasola, O. A., & Otto, E. (2023). Beneath the Surface: Uncovering Heavy Metal Contamination in Public Drinking Well Water and the Public Health Implications in Kaduna South LGA,3 Nigeria. International Journal of Science for Global Sustainability, 9(4), 1018-1024.

[10]. Opasola, O. A., & Otto, E. (2024). Evaluation of Heavy Metal Levels and Contamination Indices of Groundwater Sources in Kaduna South Local Government Area, Kaduna State, Northern Nigeria. J. Appl. Sci. Environ. Manage, 28(6), 1841-1852.

[11]. Ouéda, N., Tchakala, I., Sanni, S., & Bawa, M. L. (2024). Simple use of low-cost and available adsorbent for cationic dye adsorption from aqueous solution. Journal of Water Process Engineering, 45, 102512.

[12]. Patel, S. R., & Mehta, A. P. (2024). Comparative study of low-cost adsorbents for water treatment. Environmental Science and Pollution Research, 31, 1234–1245.

[13]. Prasad, K. S. B., Hussain, P. J., & Kumar, P. B. (2021). Defluorination of groundwater by low-cost adsorbents. Sustainable Environment Research, 31, 25.

[14]. Rangabhashiyam, S., Lins, P. V. D. S., & Annadurai, G. (2014). Application of Annona squamosa seed adsorbent for the removal of dye from wastewater. Industrial & Engineering Chemistry Research, 53(16), 6790–6800.

[15]. Saha, P., & Chowdhury, S. (2011). Insight into adsorption thermodynamics. In Adsorption processes for water treatment (pp. 55-79). CRC press.

[16]. Tiwari, B. B., Tiwari, S., Kim, M., & Kang, S. C. (2017). Application of agricultural waste for the removal of heavy metals from aquatic environments. Clean Technologies and Environmental Policy, 19, 1003-1016.

[17]. Wagh, V. M., Panaskar, D. B., Mukate, S. V., Gaikwad, S. K., Muley, A. A., & Varade, A. M. (2018). Health risk assessment of heavy metal contamination in groundwater of Kadava River Basin, Nashik, India. Model4 Earth System and Environment. https://doi.org/10.1007/s40808-018-0496-z

[18]. Wang, L; Tao, Y; Su, B; Wang, L; Liu, P (2022). Environmental and Health Risks Posed by Heavy Metal Contamination of Groundwater in the Sunan Coal Mine, China. Toxics, 10. https://doi.org/10.3390/toxics10070390

[19]. Yang, M, Fei, Y, Ju, Y, & LiH, M. Z. (2012). Health risk assessment of groundwater pollution—a case study of typical City in North China Plain. Journal of Earth Science,5 23(3), 335–348. https://doi.org/10.1007/s12583-012-0260-7

[20]. Yang, Z., Ge, H., Lu, W., & Long, Y. (2015). Assessment of heavy metals contamination in near-surface dust. Polish Journal of Environmental Studies, 24(4), 1817-1829.

[21]. Yeh, T.Y., Chou, C.C., Pan, C.T., 2009. Heavy metal removal within pilot-scale constructed wetlands receiving river water contaminated by confined swine operations. Desalination 2496 (1), 368–373. https://doi.org/10.1016/j. desal.2008.11.025.

[22]. Yohanna, P., Apeh, O. V., & Lawuyi, T. (2021). Analyzing the quality of ground water in Kaduna South Local Government Area, Kaduna State, Nigeria. Fudma Journal of Sciences,7 5(2), 413-418. https://doi.org/10.33003/fjs-2021-0502-631

[23]. Yussuf, N.M., Embong, Z., Abdullah, S., Masirin, M.I.M., Tajudin, S.A.A., Ahmad, S., Sahari, S.K., Anuar, A.A., Maxwell, O., 2018. The enhancement of heavy metal removal from polluted river water treatment by integrated carbon-aluminium electrodes using electrochemical method.8 IOP Conf. Ser.: Mater. Sci. Eng. 298 (1) https://doi.org/10.1088/1757-899X/298/1/012006.

[24]. Zhang, Y, Wu, J & Xu, B (2018) Human health risk assessment of groundwater nitrogen pollution in Jinghui canal irrigation area of the loess region,9 northwest China. Environmental Earth10

Sciences 77(7):273. https://doi.org/10.1007/s12665-018-7448-4
[25]. Zeng, G., Liang, J., Guo, S., Shi, L., Xiang, L., Li, X., Du, C., 2009. Spatial analysis of human health risk associated with ingesting manganese in Huangxing Town...11