Exp. Theo. NANOTECHNOLOGY 10 (2026) 1203-1217 https://doi.org/10.56053/10.3.1203

Nanoscale interpretation of sewage-derived heavy metal contamination and its impact on algal communities in Euphrates River sediments, Anbar Governorate, Iraq

Ruqaya Shaker Mahmood[1], *Mohammed Abdulhadi Sarhan*[2], *Baydaa Amer Mohammed*[3], *M. Al Nuaimi*[1], *Mustafa Nuhad Al-Darraji*[4], *Tarek Saidani*[5], *Aasim Jasim Hussein*[6], *Mohammed Rajih Jassim*[7], *Suham Al-Deen Khairy Hasson Al-Ali*[8], *Mazin Haithem Razuky*[9], *Youssef Ben-Ali*[10], *Taha Rashid*[11]

[1]College of Applied Sciences, University of Technology- Iraq, Baghdad, Iraq
[2]Mathematics Science Department, College of Science, Mustansiriyah University, Baghdad, Iraq
[3]Department of Missions and Cultural Relations, Al-Iraqia University, Baghdad, Iraq
[4]Department of Biology, Science College, University of Al-Anbar, Anbar, Iraq
[5]Physics of Materials and optoelectronic Components Laboratory, Faculty of Exact Sciences, Akli Mohaned Oulhadj University of Bouira, Bouira, 10000, Algeria
[6]Department of Biology, College Of Education for Pure Sciences, University of Al-Anbar, Iraq
[7]College of Production Engineering and Metallurgy, University of Technology- Iraq, Baghdad, Iraq
[8]Department of Finance and Banking, Al-Iraqia Science University, Baghdad, Iraq
[9]Biomedical Informatics College, University of Information Technology and Communications, Baghdad, Iraq
[10]Laboratory of Materials, Waves, Energy and Environment, Team of Waves, Acoustics, Photonics and Materials, Mohamed I University, Oujda, Morocco
[11]School of Electrical Engineering, Universiti Teknologi Malaysia, UTM Johor Bahru, 81310, Johor Bahru, Malaysia
[*]) Email: rasheed.mohammed40@yahoo.com

Received 22/4/2026, *Received in revised form* 13/5/2026, *Accepted* 18/6/2026, *Published* 15/7/2026

Heavy metal pollution is a severe environmental and health problem, especially in the city and industrial areas where the wastewater from the industries is untreated and comes with the toxic metals that leak into the aquatic ecosystems. The study that is carried out between December 2023 and

December 2024 is aimed at the seasonal collection (summer, autumn, winter, and spring) of environmental samples, water and sediments, precisely, from five middle locations along the Euphrates River in Anbar, Iraq: Haditha, Anah, Rawa, Al-Ubaidi, and Al-Qa'im, which are located at – approximately– 34.14049, 34.41008, 34.55312, 34.41542, and 34.38621 latitudes, respectively. The main reasons for selecting these places are hazardous waste exposure, pollution sources, and lack of environmental protection. The main goal of the research is to find out the differences in the spatial and seasonal distributions of the heavy metal elements zinc (Zn), chromium (Cr), and nickel (Ni) in riverbed sediments. In addition, parameter such as pH presence are taken into account as factor of water quality. In addition to bulk chemical assessment, a nano-scale interpretative framework is applied to evaluate the role of fine-grained sediment particles in controlling heavy metal retention and bioavailability. Predicted nano-scale enrichment patterns indicate stronger association of Zn and Cr with reactive sediment surfaces at sewage-impacted sites, enhancing ecological stress on algal communities. This approach provides a mechanistic perspective linking sediment chemistry, nano-scale processes, and biological responses.

Keywords: Seasons, Anbar, algae, Al-Qaim, heavy metals.

1. INTRODUCTION

Recent advances in environmental nanotechnology have highlighted the importance of nano-scale processes in controlling the fate, transport, and toxicity of contaminants in aquatic ecosystems. At the nano-scale, heavy metals interact strongly with fine sediment particles such as clay minerals, metal oxides, and organic colloids due to their high surface-area-to-volume ratios and surface reactivity. These nano-sized fractions act as primary carriers for metals such as Zn, Cr, and Ni, influencing their mobility, persistence, and bioavailability. Moreover, nano–bio interactions between sediment-bound metals and algal cells can enhance metal uptake and physiological stress. Incorporating a nano-scale perspective therefore improves understanding of how sewage-derived heavy metals affect sediment quality and algal communities in river systems such as the Euphrates River. The Euphrates River, extending nearly 2,800 km, is one of Southwest Asia's principal rivers, with about 35% of its course flowing through Iraq and irrigating 65,831 km^2 of land at a discharge rate of 818 m^3/sec [1-3]. Beyond its agricultural importance, the river sustains aquatic ecosystems but also transports pollutants from industrial, urban, and agricultural sources [4-6]. Heavy metals and hazardous substances accumulate in fish and other organisms through biomagnification, threatening ecosystem balance and human health [7-9]. Algae, as sensitive bio-indicators, reveal water quality shifts caused by pollution. Monitoring such biological responses provides critical insights for sustainable water management and ecosystem protection [10, 11]. Water pollution is among the most pressing environmental issues worldwide, particularly in regions experiencing rapid urbanization and industrial growth [12, 13]. Rivers, as key freshwater resources, often receive untreated sewage, industrial effluents, and agricultural runoff, resulting in severe contamination [14-16]. In Iraq, the Euphrates River is crucial for agriculture, drinking water, and ecosystem services, yet it faces alarming pollution levels due to population expansion and the absence of adequate wastewater treatment [17, 19]. The discharge of pollutants has degraded habitats, endangering both humans and aquatic species. This study emphasizes supplementing chemical analyses with biological indicators to better assess ecological health and support sustainable river restoration [20-23]. Heavy metals such as Zn, Ni, Cu, Fe, Cr, and Co are common pollutants in aquatic ecosystems due to domestic, agricultural, and industrial activities [24-27]. These elements are stable, non-biodegradable, and accumulate in soil, water, and organisms, posing serious risks to both animals and humans [28-30]. Elevated concentrations disrupt vital biological processes; induce oxidative stress, and bioaccumulate through the food chain [31]. In rivers, sediments act as both sinks and secondary sources of metals, influencing microbial life and reducing biodiversity [32]. Such disturbances impair benthic communities and ecosystem balance [33]. This study examines heavy metal accumulation in Euphrates River sediments to evaluate ecological impacts [34-36]. The Euphrates River is a lifeline for agriculture, industry, and households in Iraq, particularly in Anbar Governorate, where communities rely heavily on its resources [37-40]. However, rapid urbanization, population growth, and unresolved waste management have severely degraded water quality. Industrial effluents and untreated sewage are discharged directly into the river, making them major pollution sources [41]. Seasonal variations in flow, temperature, and human activity further influence pollutant transport and distribution, creating spatial disparities in contamination [42]. Understanding these local environmental conditions is essential for developing effective policies, targeted monitoring strategies, and region-specific water management plans to safeguard ecological and human health [43]. Research on the Euphrates River remains fragmented, often limited to chemical monitoring of water or broad assessments of biological diversity without linking pollution sources to ecological effects [44]. In particular, little is known about how heavy metal contamination in sediments influences algal community structures, especially in Anbar Governorate, where weak environmental regulation and extensive sewage discharge exacerbate pollution [45]. Moreover, temporal and spatial pollution profiles are poorly studied, hindering effective management. This investigation addresses these gaps by integrating chemical and biological indicators to provide a three-dimensional assessment of river health, offering a model for improved environmental monitoring and policy decisions [46-50]. The present study focuses on assessing the influence of sewage-derived contaminants, particularly heavy metals, on algal communities and sediment quality in the Euphrates River, Anbar Governorate. Using a multi-parameter approach, it evaluates water pH, concentrations of Zn, Cr, and Ni in sediments, and seasonal variations in algal diversity. By linking algal distribution with chemical data from water and sediments, the study identifies the ecological consequences of pollution and pinpoints areas most in need of intervention. Ultimately, the findings provide a foundation for rational strategies aimed at environmental monitoring, pollution control, and future rehabilitation of the Euphrates River ecosystem in Iraq. This article examines the spatial distribution of heavy metals in river sediments along the western Euphrates in Iraq, with parallel analysis of water chemistry, focusing on nitrates and phosphates as key pollution indicators. Sampling is conducted systematically at five locations—Haditha, Anah, Rawa, Al-Ubaidi, and Al-Qa'im—across four seasons (summer, autumn, winter, and spring) during two consecutive years (December 2023–December 2024). At each site, samples are collected before, after, and at estuary mouths to capture spatial variation. Statistical analyses are performed using SPSS, applying ANOVA to assess the significance of seasonal and spatial differences in pollution patterns and water quality dynamics.

2. MATERIALS AND METHODS

One of the five regions in the western part of Anbar Governorate, Iraq, had river samples taken near sewage estuary sediments, which directly lead to the main river. Geolocation (GPS) turned out to be the same as Table 1.

Table 1 Where the study is intended to happen and the respective check-in points.

Site no.	City	latitude Indicator (E°)	LongituI Indicator (N°)
1	Haditha	34.14049	42.3568
2	Anah	34.41008	41.90234
3	Rawa	34.55312	41.89541
4	Al-Ubaidi	34.41542	41.23523
5	Al-Qa'im	34.38621	41.04366

In number (1), is the beginning; in the number (2), before; and in the number (3), after of the estuary. The map in Figure 1 demonstrates that the spots are situated roughly 200 km² apart. It is at exactly these locations that the wastewater is discharged into the river, which is also populated by a huge number of people in the adjacent rural land.

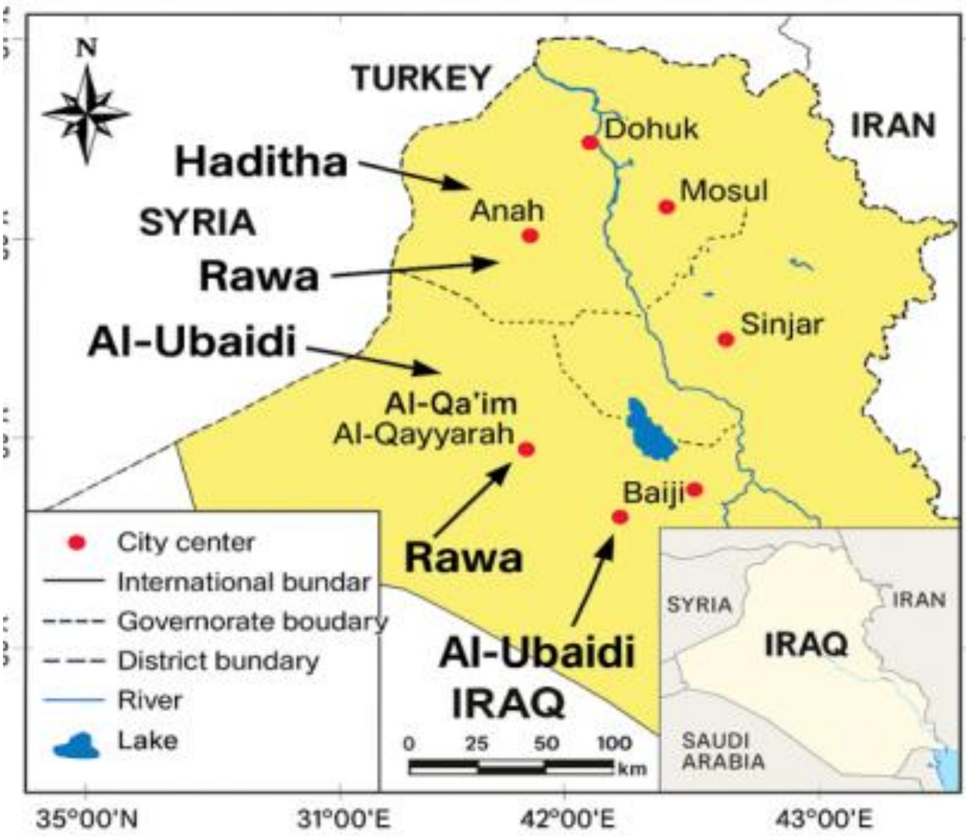

Figure 1 The Euphrates River flows across western Iraq from the point it enters near the town of Al-Qaim and continues to the city of Haditha.

The river water samples are collected by running the Ekman device into the water and then dislodging the water surface by applying the hook and scraping machines. The samples are collected from the river regions (1), (2), and (3) for the entire year's seasons (autumn, winter, spring, and summer) of 2023 to 2024. These parts of the river are recognized as water-testing regions. The examination of sediments' physical and chemical properties is done in those places of the river by means of procedures given in Table 2.

Table 2 Chemical compounds and heavy metals are tested for.

No.	Parameter	The units
1	pH	
7	Zinc (Zn)	(mg/Kg)
8	Chrome (Cr)	(mg/Kg)
9	Nickel (Ni)	(mg/Kg)

2.1 Diagnosis of heavy metals in sediments

The quantity of harmful metals (HMs: Zn, Cr, Ni) is defined by pouring some clay on a surface and letting it come in contact with the atmosphere for 5-6 hours; then it is taken to a temperature of 65-70°C in the oven for the purpose of water removal and clay drying, in addition to not causing the existing components to be burnt, and being ground and classified by size. Upon receiving said new form, the first thing we do with the 1 g of this powder is that we add it little by little to 10 ml of nitric acid and then place that mixture onto a hotplate with a temperature of 90°C for about 45 minutes, followed by a temperature increase to 150°C for a period of 4 hours to be sure about the complete digestion of the sample. By now, we are monitoring the dry samples and making sure they are still dry. After this, the samples themselves are cooled down to room temperature, then they are filtered, and 50 ml of distilled water is added for filtration. At the end of the whole process, they are packed in plastic containers and kept in the refrigerator until the minerals have been analyzed. The minerals are quantified by the Atomic Absorption machine, SHIMADZU 670 model, which is designed in Japan.

2.2 PH measures in water

Out of the clay sample, 10 ml is combined with 40 ml of pure water at a speed of 1:4 ml, then we removed the impurities by using filter papers to get a more transparent solution, and a Hanna Instruments Model 90 USA digital portable pH meter is the one used to take the measurement. The tool is properly set to the exact condition of the temperature by relying on the buffer solutions with 4, 7, and 9 values, at the same time calibrating the thermometers.

2.3 Statistical analysis

The SPSS software data is analyzed to perform the ANOVA test that is run to determine whether the differences between the variables are significant or not. The test regarding the ANOVA phase is done. The purpose of the whole thing is to know if there are any big differences in the variables (physical and chemical properties) from the space and time of the four seasons of the year (i.e., the ones carried out of the variable) with regard to the spatial and temporal changes of the four seasons. Moreover, the mean (M), standard deviation (SD), Least Significant Difference (L.S.D.), Pearson Correlation Coefficient (R), and P-value from Pearson (R) of the whole tested numbers have been calculated by the formulas provided in [25,26].

2.4. Nano-scale interpretative framework and predicted assessment

Although no direct nano-particle characterization techniques are applied, nanotechnology concepts are incorporated through a predictive and interpretative framework based on sediment geochemistry. The analysis focused on the inferred role of nano-sized sediment fractions, including clay minerals and metal oxides, which are known to dominate heavy metal adsorption processes. Bulk concentrations of Zn, Cr, and Ni measured by atomic absorption spectrophotometry are used as proxy indicators for potential nano-associated metal fractions.

Predicted nano-scale enrichment factors are derived by comparing site-specific metal concentrations relative to reference locations with lower anthropogenic impact. Seasonal pH conditions and spatial proximity to sewage estuaries are incorporated to assess their influence on adsorption–desorption behavior at the nano–sediment interface. This approach allows evaluation of nano-mediated metal behavior without requiring direct nano-fraction separation.

3. RESULTS AND DISCUSSION

In Figure 2, we can notice that locally there are not any obvious pH changes, which is manifested in turning all the values of pH into an attracted point simultaneously in all stations, as well as the arithmetic analysis of data showing no difference to be significant between them. The transformation of pH of the water is due to the acid-base buffer nature of the aquatic environment. The pH is also seen to be the highest in the upper, lower, and before estuary of the Euphrates River in the summer season for the places Haditha, Anah, Rawa, Al-Ubidi, and Al-Qa'im, which is 8.2, 8.12, and 8.24, respectively, while for the same places in the autumn season, it is 8, 8.1, and 7.8, respectively, and for the same places in the winter season, it is 8, 8.1, and 8.04, respectively, and for the same places in the spring season, it is 8.24, 8.5, and 8.14, respectively.

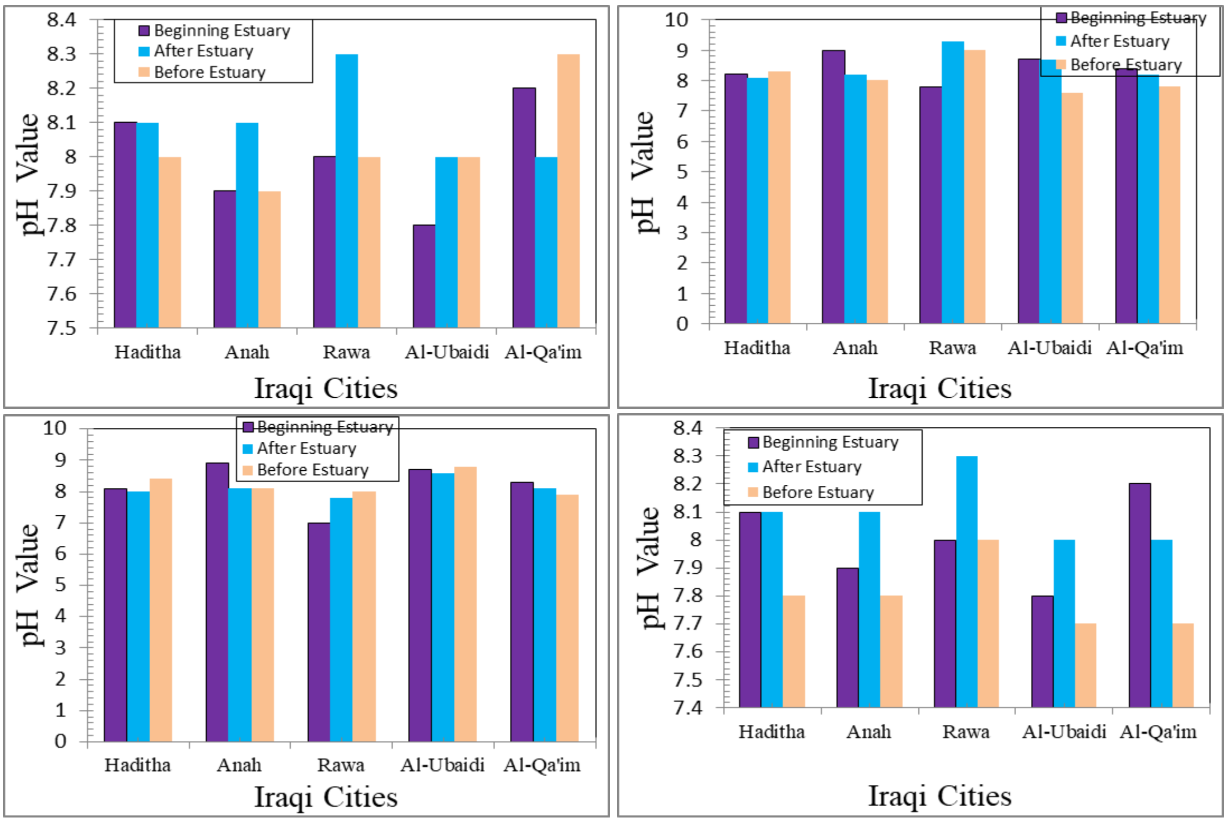

Figure 2 The pH levels of the different environments and 4 seasons, namely (a) winter, (b) spring, (c) summer, and (d) autumn.

It is seen that the average pH at the estuary, upstream and downstream of the Euphrates River at the beginning, after the estuary, and before the estuary is 1091, 735.6, and 1179 for the Haditha, Anah, Rawa, Al-Ubidi, and Al-Qaim locations, respectively, in the summer season, while the locations in the autumn season are 626.2, 423.4, and 676.4; the locations in the winter season are 674.6, 409.8, and 778.8; and the locations in the spring season are 1091.8, 685, and 1129, respectively.
Based on Figure 3, the zinc concentration levels all over the survey areas in all seasons still maintain the same level of similarity.

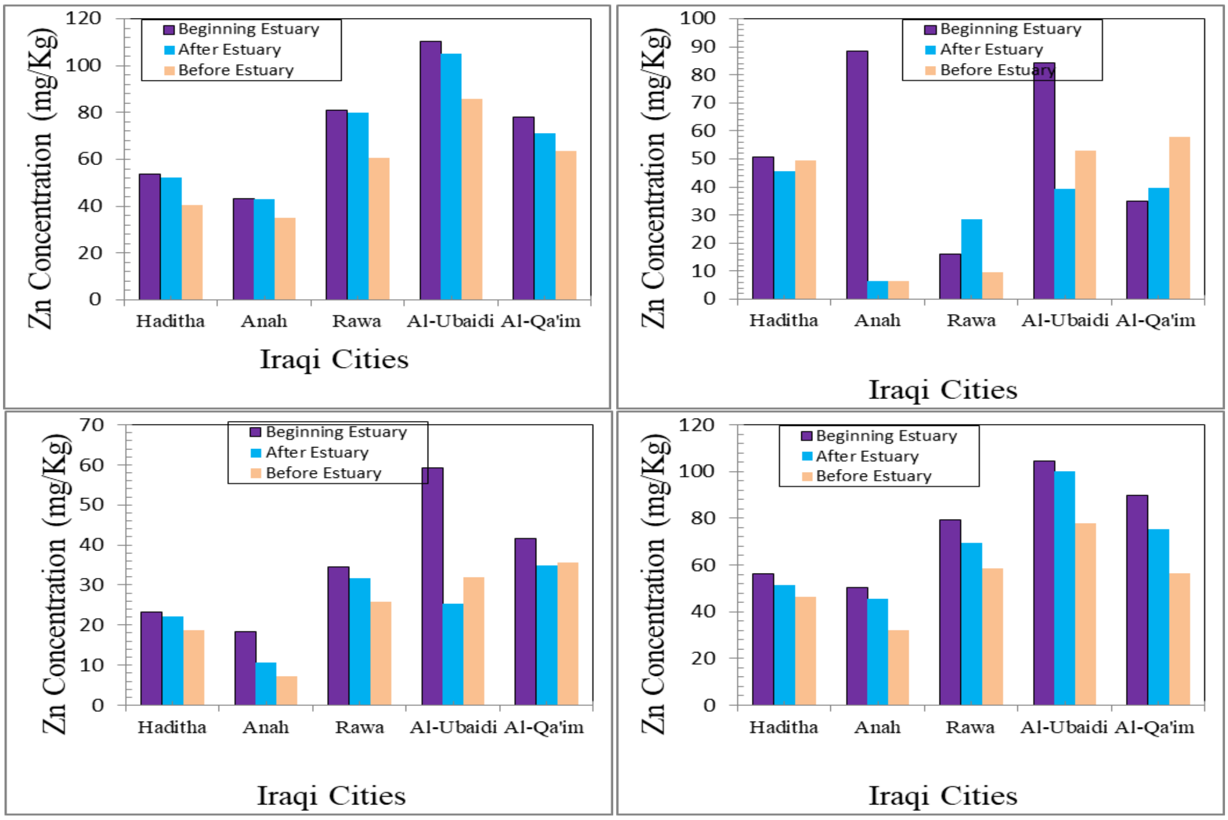

Figure 3 Zinc levels of the different environments and 4 seasons, namely (a) winter, (b) spring, (c) summer, and (d) autumn.

At Green Upstream, the average zinc (Zn) value is 73.252, 70.286 mid-way through but before the mouth of the Euphrates River, and 57.164 km in places like Haditha, Anah, Rawa, Al-Ubidi, and Al-Qa'im during this period is not disclosed, but in autumn it dropped to 54.968, 32.022, and 35.386 km, respectively; in the winter season it is 35.432, 24.977, and 23.837 km; and in the spring season it is 76.02, 68.33, and 54.284 km, respectively. According to Figure 4, the parallelism of Cr levels in rates from all locations is observed in all seasons covered in the study.

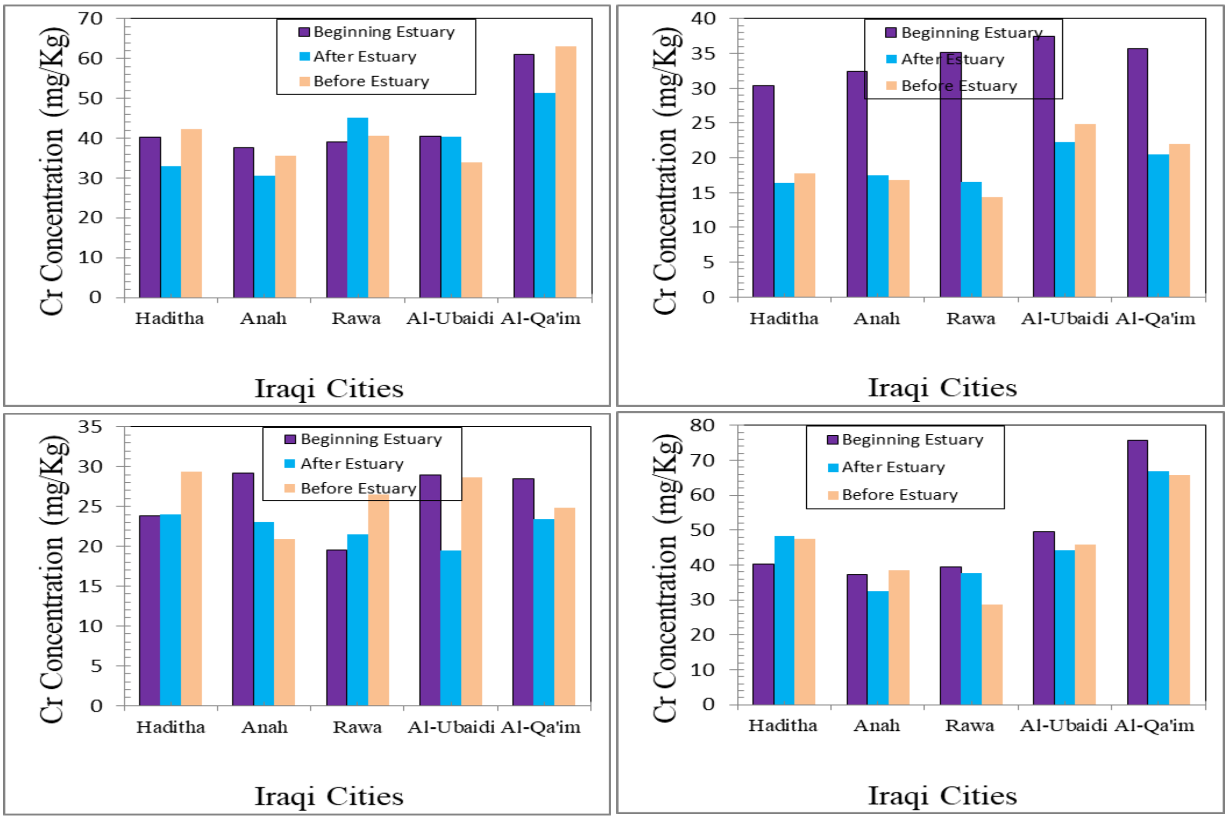

Figure 4 Curium levels of the different environments and 4 seasons, namely (a) winter, (b) spring, (c) summer, and (d) autumn.

There is a measurement done at the Euphrates River where such values as the average amount of curium (Cr) are sun-checked. The cases are collected in the regions of Haditha, Anah, Rawa, Al-Ubidi, and Al-Qa'im before and after the estuary in summer at these 3 numbers (43.738, 40.114, and 43.096), where the numbers represent mean values at which locations the Cr chemical element is determined, while the appeared numbers represent the results of autumn, winter, and spring seasons, respectively. The relevant numbers in autumn are 34.196, 18.627, and 19.1638, and in winter, the values are 26.0026, 22.314, and 26.0664; likewise, in spring, the amounts are 48.5, 45.922, and 45.292. It is evident from Figure 5 that the rates of nickel concentrations move towards close values in all the study sites and seasons.

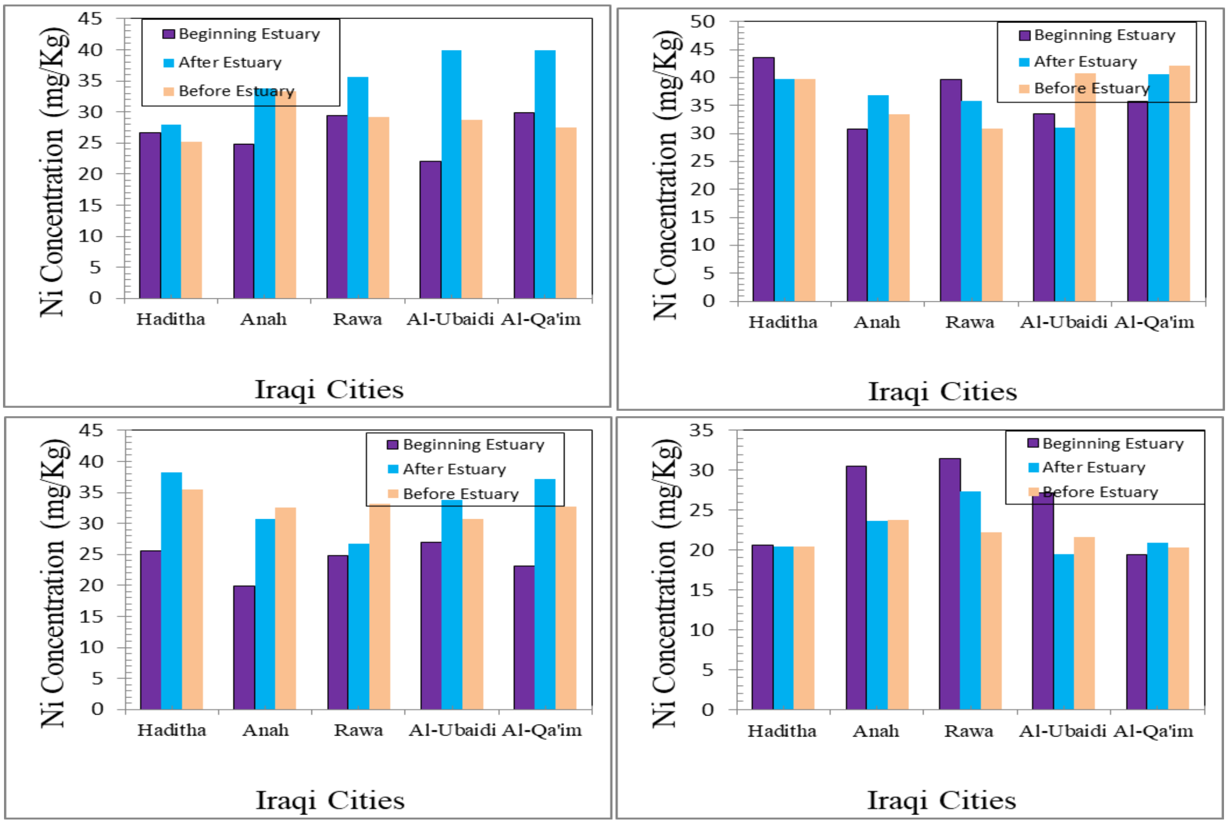

Figure 5 Nickel levels of the different environments and 4 seasons, namely (a) winter, (b) spring, (c) summer, and (d) autumn.

It is observed that the mean of nickel (Ni) content at Haditha, Anah, Rawa, Al-Ubidi, and Al-Qa'im, at the point of entrance and after the estuary of the Euphrates River, in the summer season, is 26.558, 35.458, and 28.794, respectively, while in the autumn season the values are 36.652, 36.794, and 37.382; in the winter season the values are 24.054, 33.31, and 32.9468; and in the spring season the values for these locations are 25.836, 22.382, and 21.692, respectively.

Predicted nano-scale enrichment analysis indicates spatial variability in the association of Zn, Cr, and Ni with fine sediment particles along the Euphrates River. Higher enrichment factors are observed at sewage-impacted sites, particularly Anah and Rawa, reflecting strong adsorption of metals onto reactive nano-sized sediment surfaces. Zinc exhibited the highest predicted enrichment, followed by chromium and nickel, suggesting stronger surface affinity and retention behavior. In contrast, lower enrichment factors are predicted at Haditha and Al-Qa'im, indicating reduced anthropogenic influence and weaker nano-mediated accumulation. Table 3 presents the predicted nano-scale enrichment factors of Zn, Cr, and Ni in sediments across the five sampling sites along the Euphrates River, highlighting spatial differences associated with sewage discharge intensity. The values represent relative enrichment trends derived from bulk metal concentrations, spatial position (upstream, estuary, downstream), and seasonal pH conditions, and reflect the potential association of heavy metals with reactive nano-sized sediment particles rather than direct nano-fraction measurements. Enrichment factors represent predicted relative accumulation of metals in the nano-sized sediment fraction based on observed spatial trends, pH conditions, and sewage impact intensity, rather than direct nano-fraction measurements.

Table 3 Nano-scale enrichment factors of heavy metals in Euphrates River sediments.

Site	Zn Enrichment	Cr Enrichment	Ni Enrichment
Haditha	1.2	1.1	1.0
Anah	1.6	1.5	1.3
Rawa	1.8	1.7	1.4
Al-Ubaidi	1.5	1.4	1.2
Al-Qa'im	1.1	1.0	0.9

Figure 6(a) shows the linear variation of predicted nano-scale enrichment factors of Zn, Cr, and Ni across the five sampling sites along the Euphrates River. The plot highlights a pronounced increase in enrichment from Haditha toward Anah and Rawa, followed by a gradual decline at Al-Ubaidi and Al-Qa'im. The use of discrete markers emphasizes site-specific differences, while the connecting lines illustrate consistent spatial trends among the three metals. Figure 6(b) presents the same predicted nano-scale enrichment data using a radar (spider) plot, allowing simultaneous comparison of metal enrichment patterns at each site. This representation clearly demonstrates the dominance of Zn enrichment relative to Cr and Ni at all locations and visually emphasizes the larger pollution footprint at Anah and Rawa. The compact radial layout facilitates comparison of multi-metal behavior and reinforces the spatial contrasts observed in the linear plot.

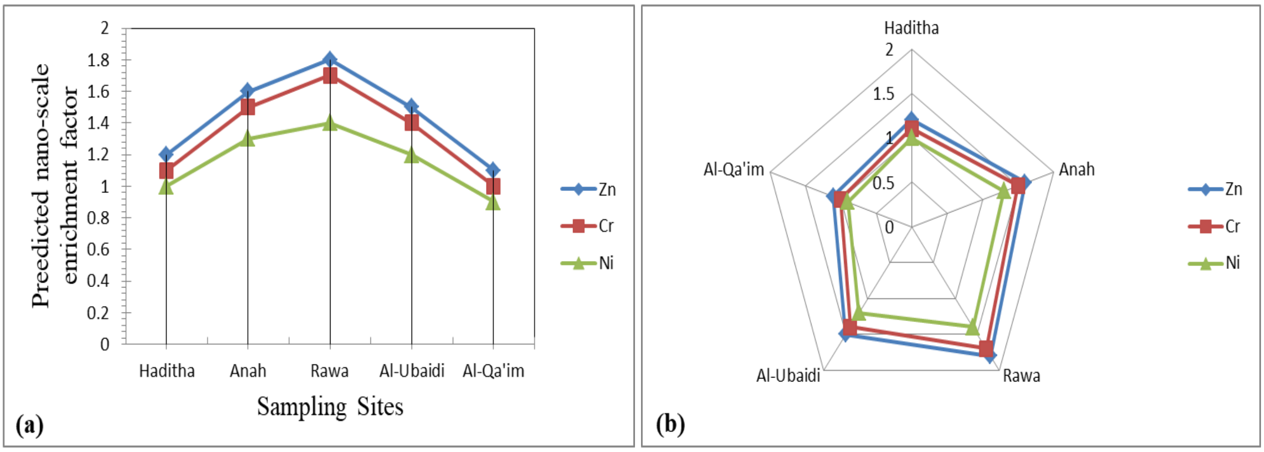

Figure 6 (a) Linear plots showing the spatial variation of predicted nano-scale enrichment factors of Zn, Cr, and Ni across the five sampling sites along the Euphrates River, highlighting higher enrichment at sewage-impacted locations (Anah and Rawa) and lower enrichment at less impacted sites (Haditha and Al-Qa'im), and (b) Radar plot representation of the same predicted nano-scale enrichment data, illustrating the relative dominance of Zn enrichment compared to Cr and Ni at all sites and emphasizing spatial contrasts in multi-metal enrichment patterns.

Figure 6 illustrates clear spatial differences in predicted nano-scale enrichment of heavy metals across the Euphrates River sampling sites. Higher enrichment values are observed at Anah and Rawa, identifying these locations as pollution hotspots influenced by continuous sewage discharge and enhanced metal adsorption onto reactive nano-sized sediment particles. In contrast, Haditha and Al-Qa'im exhibit lower predicted enrichment factors, indicating comparatively reduced anthropogenic impact and allowing these sites to function as reference or less-impacted locations. Across all sites, the enrichment pattern follows the order Zn > Cr > Ni, reflecting differences in adsorption affinity and surface reactivity of these metals, which is consistent with both established sediment geochemistry principles and the measured bulk concentration trends observed in this study.

The test results are of such magnitude that it would be difficult to imagine the situation if it is not as expected. Apparently May and October bear quite different pH values [38]. Elevated pH levels during the photosynthesis by phytoplankton, aquatic organisms, and aquatic plants that are in bloom are mainly due to the absorption of CO2 from water, a process that eventually results in an increase of pH values. On the other hand, the changes in the electrical conductivity values of each site are displayed in Figure 3, and a clear trend is then confirmed for all seasons and all sites. As a consequence of the zero variability in electrical conductivity, the probable reason is the abovementioned human activities. The mentioned factors could have the biggest influence on this not low value [39-42].

It is certainly noticed without fail that there existed completely opposite pH levels at all sites operated by the present research, such that it is indicated with a p-value less than 0.05 that the discrepancies are statistically significant, and on most/all occasions this is the case during the autumn season (in site No. 9 with a range of 8.6 and in site No. 1 with a range of 7.6), and the highest during the winter season is in location No. 5/9 with a range of 8.9 and the lowest in location No.⅓ with a range of 7, and the maximum during the spring is in location No. 1 with a range of 8.9. and the minimum in the (3) site with a border of (7), and the highest in the (1) site with a border of (9.6), which is (1, 7) with the least (7.3), and Similarity pH rates are brought about by the buffering capability of the water ecosystem and the mass of the plant, especially phytoplankton, and their function of the HCO_3-related adjustment of relationship being the reason for the convergence of pH rates... the change in pH may be attributed to the increased number of plankton, which are water plants whose rapid multiplication and the phytoplankton photosynthesis can heavily. The river alkalinity of the Euphrates is extensively sourced from natural water, which contains the dissolved carbonate and bicarbonate ions [43-45].

The results of the Zn concentration analysis showed that a p-value < 0.05 is significant, meaning that different sites are significantly different. In this context, the highest concentrations are observed at No. 9 in the autumn season, with the value of 140.3 ppm lower than 43.48 ppm in No. 4, respectively. In addition, the maximum concentration is at No. 9 with 135.52 ppm in the winter. The lowest concentration is in No. 5, with a reading of 48.8 ppm. The peak of 105.23 ppm is in the spring at No. 3, and 45.47 ppm is the bottom at No. 6. Thus, the highest changes are achieved in the summer in No. 3. The contamination level at the site is about 130.85 ppm, while it is the least at site No. 4, i.e., 40.55 ppm. Exceptional elevation in zinc in the sediments of those four locations at any season, in addition to the rise of zinc concentrations reported to be 150-300 ppm, which is the lower limit of zinc pollution estimated by the World Health Organization, is the confirmatory evidence of the station-list breakage in waste [46, 47]. A possible explanation for the increment in the levels of zinc in the stations can be the discharging of uncontrolled household, municipal, and industrial wastewater into the Euphrates River, which happens to originate from the zinc pollution of the river (Zn) [48]. Also, it can be the presence of organic waste excreted by animals or frequently using pesticides, which are sources of zinc that contributed to the water [35].

The statistical evaluation of Cr concentrations led to a conclusion that all obtained p-values are in fact less than as small as 0.05, thus showing significant differences between all sites. Hence, the highest numbers are observed in autumn at site No. 9, with a note of up to 20.86 ppm, and the fewest counts are registered at site No. 6, with a figure of 6.45 ppm. But the record highs of the fall season are also at the (9) location, with a report of (17.35 ppm). The record lows are only in the (7) location with a report of (9.01 ppm). The chromium inputs into the studied sites are considered to be polluted, and the cause is sewage that passes through soil and the urban areas. The soil in Al-Iraqi is characterized by the high reactivity of the alkaline condition, which, under the influence of the OH^- ion in solution, leads to the adsorption of heavy metals. In this regard, the results confirmed a noteworthy elevation in the chromium concentrations in the sediments of the study area, thereby disclosing that the sites are, in fact, contaminated with the chromium element. -5 ppm) [49].

The results in the (Ni) figures reveal clear spatial variations in concentration values across the five sampling sites along the Euphrates River. Haditha and Al-Qa'im show relatively stable and low values (around 20), which indicates limited influence of local pollution sources and suggests that these regions either have fewer anthropogenic discharges or benefit from natural dilution processes. In contrast, Anah and Rawa recorded the highest concentrations at the beginning estuary (30.56 and 31.48, respectively), reflecting the presence of untreated sewage, agricultural runoff, or industrial effluents entering the river at these points [50]. The decline observed after the estuary at both locations highlights the river's natural self-purification capacity through sedimentation, dilution, and uptake by aquatic organisms such as algae. Al-Ubaidi shows a particularly sharp decrease from 27.13 at the beginning to 19.53 after the estuary, suggesting rapid pollutant dispersion or strong biological activity that reduces contaminant levels [44, 50]. Statistical analysis using ANOVA confirmed that these differences between sites and sampling positions are significant ($p < 0.05$), indicating that spatial variability is strongly influenced by local pollution inputs and hydrological conditions. Overall, the data demonstrate that Anah and Rawa represent pollution hotspots, while Haditha and Al-Qa'im are relatively less impacted and can serve as baseline reference sites for ecological monitoring. The predicted nano-scale enrichment patterns provide mechanistic insight into the observed bulk metal distributions. Elevated enrichment at sewage-affected sites suggests that fine-grained sediments act as long-term sinks for heavy metals through adsorption onto reactive nano-surfaces. Seasonal alkalinity enhances negative surface charge, favoring metal retention. Furthermore, nano-associated metals are more bioavailable to algae, explaining observed ecological stress and reinforcing the suitability of algal communities as indicators of nano-mediated pollution processes.

4. CONCLUSIONS

In the Anbar Governorate, the western part of Iraq (Haditha, Anah, Rawa, Al-Ubaidi, Al-Qaim), a survey of the Euphrates River was carried out. For each location, there were three spots (beginning, before, and after the esturay), and it even inquired about the changes of the river during four seasons (summer, autumn, winter, and spring) starting from December 2023 to December 2024. The river Euphrates was the identity of the project, which was the waste of the river from nature and serious heavy metal pollution or the absence of it. The point was to figure out the presence of various heavy metals (Zn, Cr, and Ni) in the sediments of the water bodies located on the western side of Iraq. The sequence of metals in the sediments was given as Zn<Cr<Ni. Additionally, the physicochemical parameters of the wetland water (that is, pH, electrical conductivity, nitrates, and phosphates) were

measured. The collected data were elaborated by a statistical methodology, SPSS, using the software (for the analysis of variance [ANOVA]). Incorporating a nano-scale interpretative framework reveals that sediment nano-fractions play a central role in regulating heavy metal retention and ecological impact in the Euphrates River. This approach strengthens the link between sediment chemistry, sewage pollution, and algal community responses, offering a foundation for future nano-informed monitoring and remediation strategies.

References

[1] F. Boudou, A. Belakredar, A. Berkane, M. RASHEED, Notulae Scientia Biologicae, 17 (2025) 12183. https://doi.org/10.55779/nsb17212183
[2] F. Boudou, A. E. Sabar, M. I. Majeed, A. M. Ibraham, R. Jamal, A. Rashid, A. Belakredar, M. Bendahmane-Salmi, M. RASHEED, R. RASHEED, T. Saidani, H. D. Al-Bahadli, Experimental and Theoretical NANOTECHNOLOGY, 10 (2026) 821. https://doi.org/10.56053/10.S.821
[3] F. Boudou, A. Guendouzi, A. Belakredar, M. RASHEED, Notulae Scientia Biologicae, 16 (2024) 13837. https://doi.org/10.55779/nsb16211837
[4] D. Kherifi, A. Keziz, M. Rasheed, A. Oueslati, Ceramics International, 50 (2024) 1. https://doi.org/10.1016/j.ceramint.2024.05.317
[5] M. Rasheed, A. Khaleefah, Materials Chemistry and Physics, 355 (2026) 132112. https://doi.org/10.1016/j.matchemphys.2026.132112
[6] G. E. Alkinani, A. R. J. Katae, M. RASHEED, Experimental and Theoretical NANOTECHNOLOGY, 10 (2026) 1027. https://doi.org/10.56053/10.S.1027
[7] M. Enneffati, B. Louati, K. Guidara, M. Rasheed, R. Barillé, Journal of Materials Science: Materials in Electronics, 29 (2018) 171. https://doi.org/10.1007/s10854-017-7901-7
[8] H. K. Aity, E. Dhahri, M. Rasheed, Ceramics International, 50 (2024) 54666. https://doi.org/10.1016/j.ceramint.2024.10.324
[9] A. A. Hateef, E. Dhahri, M. Rasheed, H. Kadhim, Z. Abbas, N. Hassan, Physics and Chemistry of Solid State, 25 (2024) 801. https://doi.org/10.15330/pcss.25.4.801-810
[10] E. Kadri, et al., Journal of Alloys and Compounds, 705 (2017) 708. https://doi.org/10.1016/j.jallcom.2017.02.117
[11] M. Rasheed, et al., Journal of Advanced Biotechnology and Experimental Therapeutics, 6 (2023) 495. https://doi.org/10.5455/jabet.2023.d144
[12] A. Aukštuolis, et al., Proceedings of the Romanian Academy Series A: Mathematics, Physics, Technical Sciences, Information Science, 18 (2017) 34. https://hal.archives-ouvertes.fr/hal-02443179
[13] F. Boudou, et al., Notulae Scientia Biologicae, 17 (2025) 12593. https://doi.org/10.55779/nsb17312593
[14] R. S. Mahmood, et al., Journal of the Mechanical Behavior of Materials, 34 (2025) 1. https://doi.org/10.1515/jmbm-2025-0040
[15] K. K. Khudair, F. Boudou, A. Mohammed, A. Sehmi, A. Belakredar, M. S. Ibrahim, Experimental and Theoretical NANOTECHNOLOGY, 10 (2026) 869. https://doi.org/10.56053/10.S.869
[16] A. R. J. Katae, H. H. Hussein, A. S. Jaber, M. A. Sarhan, M. RASHEED, Experimental and Theoretical NANOTECHNOLOGY, 10 (2026) 795. https://doi.org/10.56053/10.2.795
[17] A. R. J. Katae, H. H. Hussein, A. S. Jaber, M. A. Sarhan, M. RASHEED, Experimental and Theoretical NANOTECHNOLOGY, 10 (2026) 725. https://doi.org/10.56053/10.2.725
[18] M. Rasheed, I. Alshalal, A. A. Rashed, M. A. Sarhan, A. S. Jaber, Indonesian Journal of Electrical Engineering and Computer Science, 33 (2024) 653 https://doi.org/10.11591/ijeecs.v33.i1.pp653-660

[19] H. M. I. Al-Zuhairi, I. Alshalal, H. H. Abbood, M. Al Nuaimi, Experimental and Theoretical NANOTECHNOLOGY, 10 (2026) 855. https://doi.org/10.56053/10.S.855
[20] H. M. I. Al-Zuhairi, I. Alshalal, H. H. Abbood, M. Al Nuaimi, Experimental and Theoretical NANOTECHNOLOGY, 10 (2026) 1093. https://doi.org/10.56053/10.S.1093
[21] A. Zubaidi, L. M. Asaad, I. Alshalal, M. Rasheed, Journal of the Mechanical Behavior of Materials, 32 (2023) 1. https://doi.org/10.1515/jmbm-2022-0302
[22] A. Raghdi, M. Heraiz, M. Rasheed, A. Keziz, Journal of the Indian Chemical Society, 101 (2024) 101413. https://doi.org/10.1016/j.jics.2024.101413
[23] A. Jaber, M. Ismael, T. Rashid, M. A. Sarhan, M. Rasheed, I. M. Sala, Eureka: Physics and Engineering, 4 (2023) 29. https://doi.org/10.21303/2461-4262.2023.002770
[24] E. Kadri, M. Krichen, R. Mohammed, A. Zouari, K. Khirouni, Optical and Quantum Electronics, 48 (2016) 1. https://doi.org/10.1007/s11082-016-0812-7
[25] T. Rashid, M. M. Mokji, M. Rasheed, Journal of the Mechanical Behavior of Materials, 34 (2025) 1. https://doi.org/10.1515/jmbm-2025-0074
[26] T. Rashid, M. M. Mokji, M. Rasheed, Journal of Optics, 53 (2024) 1. https://doi.org/10.1007/s12596-024-02080-w
[27] A. J. Hussein, M. N. Al-Darraji, M. Rasheed, M. A. Sarhan, IOP Conference Series: Earth and Environmental Science, 1262 (2023) 022005. https://doi.org/10.1088/1755-1315/1262/2/022005
[28] A. J. Hussein, M. N. Al-Darraji, M. Rasheed, IOP Conference Series: Earth and Environmental Science, 1262 (2023) 022007. https://doi.org/10.1088/1755-1315/1262/2/022007
[29] M. Rasheed, M. N. Mohammedali, F. A. Sadiq, M. A. Sarhan, T. Saidani, Journal of Optics, 54 (2024) 1. https://doi.org/10.1007/s12596-024-01928-5
[30] M. Enneffati, M. Rasheed, B. Louati, K. Guidara, R. Barillé, Optical and Quantum Electronics, 51 (2019) 1. https://doi.org/10.1007/s11082-019-2015-5
[31] A. A. Abdulrahman, M. Rasheed, S. Shihab, Journal of Physics: Conference Series, 1879 (2021) 022118. https://doi.org/10.1088/1742-6596/1879/2/022118
[32] T. Saidani, M. Rasheed, I. Alshalal, A. A. Rashed, M. A. Sarhan, R. Barillé, Research on Engineering Structures and Materials, 9 (2023) 1. https://doi.org/10.17515/resm2023.21ma0922rs
[33] S. S. Batros, M. Rasheed, H. K. Aity, A. A. Hatef, T. Saidani, Materials Chemistry and Physics, 355 (2026) 132243. https://doi.org/10.1016/j.matchemphys.2026.132243
[34] Z. S. Ahmed, M. RASHEED, H. S. Ahmed, Experimental and Theoretical NANOTECHNOLOGY, 10 (2026) 329. https://doi.org/10.56053/10.s.329
[35] H. K. Aity, M. Rasheed, E. Dhahri, A. A. Hateef, T. Saidani, Journal of Materials Science, 61 (2026) 6226. https://doi.org/10.1007/s10853-026-12241-w
[36] Z. S. Ahmed, M. RASHEED, H. S. Ahmed, Experimental and Theoretical NANOTECHNOLOGY, 10 (2026) 343. https://doi.org/10.56053/10.s.343
[37] I. M. Mohammed, M. Rasheed, AIP Conference Proceedings, 3321 (2025) 020026. https://doi.org/10.1063/5.0289719
[38] A. Keziz, M. Rasheed, M. Heraiz, F. Sahnoune, A. Latif, Ceramics International, 49 (2023) 37423. https://doi.org/10.1016/j.ceramint.2023.09.068
[39] A. Khaleefah, M. RASHEED, Experimental and Theoretical NANOTECHNOLOGY, 10 (2026) 289. https://doi.org/10.56053/10.s.289
[40] A. I. A. Ali, M. RASHEED, Experimental and Theoretical NANOTECHNOLOGY, 10 (2026) 277. https://doi.org/10.56053/10.s.277
[41] A. I. A. Ali, M. RASHEED, Experimental and Theoretical NANOTECHNOLOGY, 10 (2026) 239. https://doi.org/10.56053/10.s.239
[42] T. Saidani, M. Zaabat, M. S. Aida, R. Barillé, M. Rasheed, Y. Almohamed, Journal of Materials Science: Materials in Electronics, 28 (2017) 9252. https://doi.org/10.1007/s10854-017-6660-9

[43] W. Saidi, N. Hfaidh, M. Rasheed, M. Girtan, A. Megriche, M. El Maaoui, RSC Advances, 6 (2016) 68819. https://doi.org/10.1039/c6ra15060h
[44] M. Rasheed, O. Y. Mohammed, S. Shihab, A. Al-Adili, Journal of Physics: Conference Series, 1795 (2021) 012042. https://doi.org/10.1088/1742-6596/1795/1/012042
[45] M. Rasheed, R. Barillé, Journal of Alloys and Compounds, 728 (2017) 1186. https://doi.org/10.1016/j.jallcom.2017.09.084
[46] E. Arif, R. Jamal, M. RASHEED, Experimental and Theoretical NANOTECHNOLOGY, 10 (2026) 453. https://doi.org/10.56053/10.2.453
[47] F. Dkhilalli, S. Megdiche, K. Guidara, M. Rasheed, R. Barillé, M. Megdiche, Ionics, 24 (2018) 169. https://doi.org/10.1007/s11581-017-2193-8
[48] T. Saidani, S. Mokhtari, M. Rasheed, H. Lahmar, M. Trari, Journal of the Indian Chemical Society, 103 (2026) 102499. https://doi.org/10.1016/j.jics.2026.102499
[49] M. Rasheed, S. Shihab, O. Alabdali, A. Rashid, T. Rashid, Journal of Physics: Conference Series, 1999 (2021) 012077. https://doi.org/10.1088/1742-6596/1999/1/012077
[50] M. S. Ibrahim, T. T. Issa, B. Yaqoob, E. N. Fayyadh, A. Rashid, R. S. Mahmood, Experimental and Theoretical NANOTECHNOLOGY, 10 (2026) 887. https://doi.org/10.56053/10.S.887