International Journal of Innovative Technology and Interdisciplinary Sciences
https://journals.tultech.eu/index.php/ijitis
ISSN: 2613-7305
Volume 8, Issue 3
DOI: https://doi.org/10.15157/IJITIS.2025.8.3.624-641
Received: 21.07.2025; Revised: 29.08.2025; Accepted: 31.08.2025

Research Article

Assessment of Seasonal Fluctuations in Heavy Metal and Bacterial Pollution in the Euphrates River near Najaf, Iraq

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Abstract

This research work assessed seasonal variations in physicochemical parameters, heavy metals, and bacterial contamination in the Euphrates River near Najaf, Iraq, from December 2023 to November 2024. Results revealed marked seasonal fluctuations in water temperature, ranging from 14.80 ± 2.04 °C in winter to 30.31 ± 1.01 °C in summer. Total dissolved solids (TDS) were highest in winter (924.19 ± 44.26 mg/L) and lowest in summer (652.74 ± 37.50 mg/L). While pH, dissolved oxygen (DO), and biochemical oxygen demand (BOD5) remained within international standards, TDS exceeded the World Health Organization (WHO) aesthetic guideline, and concentrations of lead and cadmium surpassed both WHO and U.S. Environmental Protection Agency (USEPA) limits. Lead concentrations increased substantially from spring (0.05 ± 0.02 mg/L) to autumn (1.47 ± 0.31 mg/L). Total coliform bacteria (TCB), indicative of faecal contamination, were present in all samples. Correlation analyses suggested that industrial effluents and untreated sewage represent common sources of heavy metals and bacterial pollutants. The findings indicate that the Euphrates River water in this region is unsuitable for direct consumption without advanced treatment and presents significant risks to human health and the aquatic ecosystem.

Keywords: Heavy Metals; Seasonal Variation; Bacterial pollution; Euphrates River

INTRODUCTION

There are several ways in which heavy metals, which are non-biodegradable and bio-accumulate in the food chain, enter the rivers. Industrial discharges and agricultural wastewater containing pesticides are among these methods, along with fertilizers and runoff [1, 2]. Local populations are the most exposed to the risks of waterborne diseases because they depend entirely on the river for their daily water needs. These diseases arise from bacterial contamination caused by untreated sewage and domestic and commercial waste [3]. Pollutants vary greatly throughout the year, influenced by seasonal changes in environmental factors such as temperatures, rainfall amounts, and water flow across the year [4]. Pollutants are concentrated in summer due to rising temperatures and reduced water discharge, while in winter there is an increase in rainfall and flow rates, thus decreasing the concentration of these pollutants [5].

Despite the widespread acknowledgment of these issues, there remains a notable lack of comprehensive, seasonal data on the combined presence of both heavy metals and bacteria in the Euphrates River, particularly within the Najaf province of Iraq. The city of Najaf and the surrounding areas rely heavily on the Kufa branch of the Euphrates River for irrigation and drinking water. Due to its important location, water quality can be monitored [6]. The study aims to fill this information gap by researching seasonal changes of bacteria and heavy metals in the Euphrates River in Najaf Province, where it provides effective data for more accurate management of water resources and protecting individual health. Many studies have found that the water quality of the Euphrates River is deteriorating due to human activity. The river water and its sediments have been found to consistently contain heavy metals such as cadmium, lead, zinc, copper, and iron [7, 8].

The middle part of the Euphrates River, which includes Najaf Governorate, revealed through the study that the concentration of lead and cadmium largely exceeds the limits set by the World Health Organization (WHO) and the United States Environmental Protection Agency (USEPA), thus exposing human health to high risks from both carcinogenic and toxic perspectives [9]. Mostly, these pollutants are produced by industrial discharges, runoff from agricultural lands, and the use of fertilizers and pesticides [10]. The Euphrates River is facing a threat from microbial pollution in addition to chemical pollution. The studies identified widespread pollution from untreated sewage and household waste due to the presence of high levels of total coliforms and faecal matter, in addition to hazardous bacteria such as Escherichia coli, Klebsiella, and Salmonella [11].

This bacterial contamination is a clear result of the weak infrastructure for wastewater treatment, as a large amount of human waste is directly discharged into the river [12]. The study that analysed water quality in the Najaf region using the Canadian Water Quality Index (CCME WQI) classified the water as 'poor' to 'marginal,' with rising levels of faecal coliforms being the primary cause of pollution, making the water unsuitable for direct human consumption [13]. Previous research accurately confirms that pollution levels vary significantly from one season to another. In the summer, water quality in the Euphrates River often deteriorates due to high temperatures, low water levels, and increased evaporation, which raises pollutants [14]. In contrast, in winter and spring, heavy rains and increased river flow tend to reduce pollution concentrations [15]. The focused study on Najaf Governorate established that pollution metrics, such as total dissolved solids (TDS), were at high levels in July compared to January, confirming the seasonal nature of the problem [16].

These results highlight the need to develop a tailored strategy for control and management that aligns with the seasons, as the risks associated with water vary throughout the year. In many aquatic environments, there is not clear correlation exists between the presence of heavy metals and coliform bacteria. Because of the relationship is complex, primarily due to their common sources of pollution and the biological mechanisms bacteria have evolved to survive in contaminated environments.

This study aims to investigate this relationship, determining if an interaction between heavy metals and total coliform bacteria (TCB) exists in the Euphrates River.

RELATED WORK

Water quality parameters are critical indicators of the health of aquatic ecosystems and human health, and numerous descriptions of water quality can be found in the scientific literature [17]. Water quality is most commonly defined as "the physical, chemical, and biological characteristics of water" and the state of water in relation to the needs of one or more biotic species and/or any human need or purpose is known as water quality [18].

Water quality prediction by employing Long Short-Term Memory (LSTM) networks, integrated with pollution indices and trend analysis. Their approach enabled the prediction of crucial water quality parameters, facilitating resource optimization and sustainable management by identifying influential factors and forecasting future pollution trends [19].

Physical Parameters include temperature, turbidity, and electrical conductivity, which affect aquatic life and water usability [20]. Water that is cloudy is called turbid and it is a measurement of how well light can travel through water. It is brought on by suspended particles in water, including silt, clay, organic matter, plankton, and other particles, and it is prohibited to have turbidity in drinking water because it makes the water appear [21].

Temperature affects chemical reactions, smells, solubility, viscosity, and palatability, and as a result, biological oxygen demand (BOD) and the processes of sedimentation and chlorination are temperature dependent and Increased sedimentation from construction and agricultural activities can reduce light penetration, affecting photosynthesis [22].

Additionally, it has an impact on how the dissolved heavy metals in water bios orb the majority of people prefer water that is between 10 and 15°C. Chemical Parameters: Key metrics such as pH, dissolved oxygen (DO), biochemical oxygen demand (BOD), and chemical oxygen demand (COD) are essential for assessing water quality. High levels of pollutants like nitrates and heavy metals (e.g., lead, arsenic) can sev0erely compromise water safety [23].

pH is one of the most important parameters of water quality, and it is defined as the negative logarithm of the hydrogen ion concentration and dissolved oxygen demand. One of the most crucial indicators of water quality in lakes, rivers, and streams is dissolved oxygen (DO). One important test for water pollution is this one [20]. The quality of the water improves with a higher dissolved oxygen concentration; Oxygen is extremely sensitive to temperature and only weakly soluble in water. For instance, the saturation concentration is 14.6 mg/L at 0°C and around 9 mg/L at 20°C [24].

Water's salinity, temperature, and pressure all affect the actual amount of dissolved oxygen, and public health is not directly impacted by dissolved oxygen, although some people find it unpleasant to drink water that contains little or no oxygen [25].

Biochemical oxygen demand (BOD)Bacteria and other microorganisms use organic substances for food as they metabolize organic material, they consume oxygen [26].

The organics are broken down into simpler compounds, such as CO_2 and H_2O, and the microbes use the energy released for growth and reproduction. When this process occurs in water, the oxygen consumed is the DO in the water, and if oxygen is not continuously replaced by natural or artificial means in the water, the DO concentration will decrease as the microbes decompose the organic materials [27].

The need for oxygen is called the biochemical oxygen demand (BOD) and the more organic material there is in the water, the higher the BOD used by the microbes will be this BOD is used as a measure of the power of sewage; strong sewage has a high BOD and weak sewage has low BOD [28]. Pollution from various sources, including industrial effluents and agricultural runoff, significantly impacts these parameters, leading to detrimental effects on both aquatic life and human populations [29].

METHODOLOGY

Study Area

The study area starts from the beginning entrance of the Euphrates River in Al – Zarqa / Al- Kufa / Najaf city until way out near of Al- Essa bridge which is the last place for this river. The samples were taken from four site at Euphrates River/Kufa city (Fig, 1). First site was at (32o0503.59N, 44o2254.59E) near Al – Zarqa water filtering station, second site was at (32o0244.58N, 44o2349.39E) near Al -Imam Ali Bridge, third site was at (32o0026.11N, 44o2554.42E) near Al -Barakiya Treatment Station and fourth site was at (31o5902.39N, 44o2654.77E) under the bridge of Al- Essa.

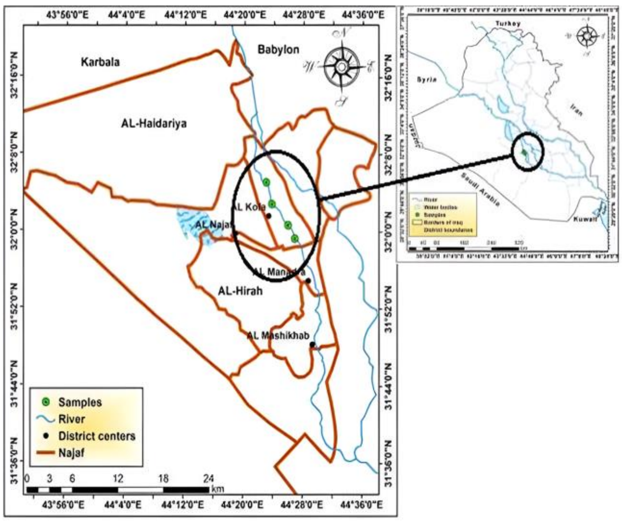

Figure 1. Location map of AL- Najaf AL- Ashraf governorate, sampling stations of the Euphrates River / Najaf province, Iraq.

Cleaning

Before conducting any analysis, all glassware in this experiment were pre-cleaned with hot water, then tap water, distilled water, and then placed in an acid bath (10 % HCl) for 24 hours. [30, 31].

Sterilization

For culture media and water that deals with bacteria sterilized by autoclaving for 15 minutes at pressure 1.5 bar and temperature 121°C. All instruments and glassware that deals with bacteria were sterilized by oven [32].

Sampling Strategy

Field observations were made for an entire hydrological year from December 2023 to November 2024 to consider the seasonal variations. The samples were collected each month at all four stations, and three replicates at each place were collected to ensure reliability and statistical confidence and thus a total of 144 samples. The sampling depth was approximately 0.5 meters below the water surface to avoid surface contamination and interference from bottom sediments. Chemical samples were collected in acid-washed 500 mL polyethylene bottles, while bacteriological samples were placed in sterile 250 mL glass bottles. Bottles were cleaned using site water prior to sampling to rule out contamination. The samples were placed directly in 4 °C coolers and transported to the lab within six hours. All the tests began within twenty-four hours to preserve the samples' integrity [32].

Parameters Analysis

The study focused on ten parameters that are physical, chemical, and biological water quality determinants. Field measurements of water temperature, pH, and total dissolved solids were taken using a WTW Multiline 3430i multiparameter probe, calibrated daily against certified standards. Dissolved oxygen was determined using the Winkler titration method and five-day biochemical oxygen demand analysed by the standard incubation method, both as recommended by APHA. Heavy metal concentrations of lead, cadmium, chromium, and nickel were measured in five-later subsamples, which were filtered through 0.45 µm cellulose nitrate membranes and acidified to a pH <2 using nitric acid. The samples were stored at 4 °C until analysis on Perkin Elmer Analyst 400 atomic absorption spectrophotometers. The detection limits of the instruments were 0.005 mg/L for lead and cadmium and 0.01 mg/L for chromium and nickel. Quality control was maintained by using blanks, duplicates, and certified reference standards, while recovery rates ranged from ninety-five to one hundred and five percent. Bacteriological examination consisted of enumeration of total coliform bacteria as the Most Probable Number on MacConkey agar at 37 °C for twenty-four to forty-eight hours and reporting the results in colony-forming units per 100 mL. Positive and negative controls were processed in every batch to be methodologically correct.

The laboratory equipment was thoroughly sterilized and cleaned for all the analyses to provide accurate results. The glassware was initially washed using hot water and detergent, followed by rinsing using distilled water, and lastly immersed in 10%

hydrochloric acid for twenty-four hours. After being removed from the acid bath, the glassware was rinsed with ultrapure deionized water and dried at 105 °C. For bacteriological examination, the equipment and culture media were sterilized either by autoclaving at 121 °C for fifteen minutes under 1.5 bar pressure or by dry oven sterilization at 160 °C for two hours. These procedures minimized the possibility of exterior contamination and maintained the validity of bacteriological results.

All data were analysed using SPSS version 24 and OriginPro 2024 to identify the descriptive and inferential aspects of seasonality. The descriptive statistics involved calculation of mean values, standard deviations, and range for all the parameters. To determine whether the seasonal difference was statistically significant, one-way Analysis of Variance (ANOVA) was employed. The general model for ANOVA can be expressed as equation (1):

$$Y_{ij} = \mu + \tau_i + \epsilon_{ij} \quad (1)$$

where Y_{ij} represents the observation of the j^{th} sample in the i^{th} season, μ is the overall mean, τ_i is the seasonal effect, and ϵ_{ij} is the random error assumed to be normally distributed with mean zero and variance σ^2.

The null hypothesis tested whether all seasonal means were equal via equation (2):

$$H_0: \mu_1 = \mu_2 = \mu_3 = \mu_4 \quad (2)$$

against the alternative that at least one mean differs. The F-ratio, used as the test statistic, was computed through equation (3):

$$F = \frac{MS_{\text{between}}}{MS_{\text{within}}} \quad (3)$$

where MS_{between} is the mean square between groups (seasons) and MS_{within} is the mean square within groups. Significance was evaluated at $\alpha = 0.05$.

When significant differences were detected, Least Significant Difference (LSD) post hoc tests were applied to compare seasonal pairs. The LSD was calculated via equation (4):

$$LSD = t_{\alpha/2, df_\epsilon} \times \sqrt{\frac{2MSE}{n}} \quad (4)$$

where $t_{\alpha/2, df_\epsilon}$ is the critical value of the t -distribution at a chosen significance level with error degrees of freedom, MSE is the mean square error, and n is the number of replicates per group.

To assess the magnitude of seasonal influence, the effect size was calculated using eta-squared (η^2), see equation (5):

$$\eta^2 = \frac{SS_{\text{between}}}{SS_{\text{total}}} \quad (5)$$

where SS_{between} is the sum of squares between groups and SS_{total} is the total sum of squares. Values of η^2 closer to one indicate stronger seasonal effects.

In addition to the univariate tests, there was the use of multivariate approaches. Multivariate dimensionality reduction and pattern detection among physical, chemical, and bacteriological parameters was performed through the use of Principal Component Analysis (PCA). The PCA was obtained from the eigen-decomposition of the standardized variables' covariance matrix, see equation (6):

$$C = \frac{1}{n-1} X^{\top} X \tag{6}$$

where X is the standardized data matrix and C is the covariance matrix. The eigenvalues and eigenvectors were computed to derive principal components, and loadings were examined to determine how much each variable was contributing towards the components.

Finally, Pearson correlation analysis was employed to quantify the degree of association between heavy metal levels and total coliform counts. The correlation coefficient r was computed through equation (7):

$$r = \frac{\sum (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum (x_i - \bar{x})^2 \sum (y_i - \bar{y})^2}} \tag{7}$$

where x_i and y_i are the paired observations for heavy metals and bacteria, respectively, and $\bar{x}, \bar{y}$ are their mean values.

Linear Regression Analysis

To further examine the correlations between bacteriological and physicochemical parameters of the Euphrates River, simple linear regression models were used. Ordinary Least Squares (OLS) regression was applied to estimate the slope and intercept for selected parameter pairs using the equation (8):

$$y_i = \beta_0 + \beta_1 x_i + \varepsilon_i, \tag{8}$$

where y_i is the dependent variable, x_i is the predictor, β_0 represents the intercept, β_1 is the slope coefficient, and ε_i is the random error term.

Three models were examined:

- Dissolved Oxygen (DO) versus Temperature - to test for the inverse relationship of oxygen solubility versus water temperature.
- Total Coliform Bacteria (TCB) versus Total Dissolved Solids (TDS) - to verify whether higher dissolved solids correlate with more bacterial contamination. A logarithmic transformation log_10(TCB+1) was applied to stabilize the variance.
- Lead (Pb) versus TDS - to verify whether dissolved solids correlate with higher heavy metal concentrations.

All seasonal mean values were input to the regression models, and the regression coefficients (β_0, β_1) were estimated. Diagnostic tests were applied to ensure that linearity, independence, and homoscedasticity assumptions were met. The regression analysis facilitated quantification of direction and strength of association between primary variables, complementing the seasonal ANOVA and correlation analyses [33, 34].

RESULTS AND DISCUSSION

As shown in Table 1, water temperature was lowest in the winter (14.80±2.04 °C) and highest in the summer (30.31±1.01 °C). The mean difference is significant at the 0.05 level, with a high F-value of 55.97.

The highest TDS concentration occurred in the winter (924.19±44.26 mg/L), while the lowest was in the summer (652.74±37.50 mg/L). The seasonal variation in TDS is highly significant, as indicated by an F-value of 50.39 and a p-value of 0.00 (Table 1).

The water's pH was slightly alkaline in all seasons, with the highest value in the winter (8.09±0.46) and the lowest in the summer (7.49±0.12). The seasonal difference for pH was significant (p-value 0.00) (Table 1). Dissolved Oxygen levels were highest during the winter (6.40±1.36 mg/L) and lowest in the autumn (4.91±1.02 mg/L). This parameter also showed a significant seasonal difference, with an F-value of 3.60 and a p-value of 0.021 (Table 1).

Biochemical Oxygen Demand values were highest in the spring (4.53±4.22 mg/L) and lowest in the summer (3.04±2.70 mg/L) (Table 1). Unlike the other parameters, the seasonal change in BOD was not statistically significant, with a high p-value of 0.742. The highest concentration of TCB was recorded in the winter (338.94 cfu/100ml) and the lowest in the summer (111.77 cfu/100ml) (Table 1). Similar to BOD, the seasonal variation was not statistically significant (p-value 0.614).

The concentrations of heavy metals also varied significantly by season. Lead concentration was lowest in the spring (0.05±0.02 mg/L) and showed a dramatic increase to its peak in the autumn (1.47±0.31 mg/L). The seasonal variation for Pb is highly significant (F-value of 35.39, p-value of ≤0.001) (Table 2). Cadmium concentration was highest in the winter (0.05±0.01 mg/L) and lowest in both summer and autumn (0.02±0.01 mg/L). This seasonal change is statistically significant (F-value of 12.54, p-value of ≤0.001) (Table 2).

Chromium levels were lowest in winter and spring (0.02±0.02 mg/L and 0.02±0.01 mg/L, respectively) and reached their peak in autumn (0.13±0.02 mg/L). The seasonal variation is highly significant (F-value of 48.15, p-value of ≤0.001) (Table 2). Nickel concentrations were lowest in the winter (0.05±0.02 mg/L) and highest in the autumn (0.13±0.03 mg/L). This seasonal difference is significant (F-value of 13.63, p-value of ≤0.001) (Table 2).

The statistical analysis (ANOVA; Table 1 & 2) indicates that the seasonal variations for most parameters including TDS, pH, DO, Temperature, Pb, Cd, Cr, and Ni were highly significant at the 0.05 level, with p-values of ≤0.001. This suggests that the seasonal changes are not due to random chance. Conversely, the seasonal differences for BOD and TCB were found to be insignificant. This is supported by their high p-values (0.742 and 0.614, respectively), which are well above the significance level. The provided data doesn't explicitly describe the correlation between parameters, but trends can be observed. For instance, DO and water temperature show an inverse relationship, with DO being highest in winter when the water is coldest, and lowest in autumn when the water is warmer.

Heavy metals and coliform bacteria frequently co-occur in aquatic systems like the Euphrates River because they are often introduced by the same anthropogenic sources [36]. Untreated industrial wastewater, sewage discharge, and urban runoff are major contributors of both types of pollutants. Industrial effluents can contain high concentrations of heavy, while sewage and agricultural runoff are rich in organic matter and faecal matter, which contain coliform bacteria.

Table 1. Physiochemical and TCB statistics during seasons of study

Parameter	Winter (Mean±SD)	Spring (Mean±SD)	Summer (Mean±SD)	Autumn (Mean±SD)
Temperature (°C)	14.80 ± 2.04	22.04 ± 5.44	30.31 ± 1.01	24.63 ± 3.68
TDS (mg/L)	924.19 ± 44.26	793.15 ± 72.51	652.74 ± 37.50	722.89 ± 69.76
pH	8.09 ± 0.46	7.87 ± 0.31	7.49 ± 0.21	7.79 ± 0.21
DO (mg/L)	6.40 ± 1.36	6.18 ± 1.17	5.56 ± 1.30	4.91 ± 1.02
BOD_5 (mg/L)	4.42 ± 4.25	4.53 ± 4.22	3.04 ± 2.70	3.97 ± 3.58
TCB (cfu/100ml)	174.36 ± 286.45	141.33 ± 333.00	111.77 ± 159.03	200.00 ± 228.46

Table 2. ANOVA Results for Heavy Metals across Seasons

Heavy Metal	F-value	p-value	Significance	Interpretation
Pb (mg/L)	96.4	<0.001	***	Lead varied significantly with seasons, with autumn showing the highest values far above WHO/USEPA standards.
Cd (mg/L)	11.2	0.002	**	Cadmium differences were statistically significant; slightly higher in winter but still consistently exceeding safe limits.
Cr (mg/L)	23.5	<0.001	***	Chromium showed strong seasonal differences, with autumn concentrations peaking due to industrial discharges.
Ni (mg/L)	15.7	<0.001	***	Nickel concentrations differed significantly, highest in autumn, reflecting seasonal accumulation from anthropogenic inputs.

As these pollutants enter the river from a common point, they are found together, leading to a strong statistical correlation in water samples. While heavy metals can be toxic to bacteria at high concentrations, many bacterial species, including coliforms, have developed sophisticated mechanisms to tolerate or even thrive in metal-rich environments. This leads to a fascinating and well-documented biological correlation.

Figure 2 shows the seasonal variation of the heavy metals in the Euphrates River. The maximum value of lead occurred in autumn (1.47 mg/L), far above the permissible limit, and the minimum value occurred in spring (0.05 mg/L). Chromium and nickel occurred at the highest value during autumn, showing seasonal accumulation by industrial and agricultural sources. Cadmium, although lower in absolute values, overran international standards in all seasons, particularly winter. From the heatmap, autumn was determined to be the most critical season of heavy metal contamination.

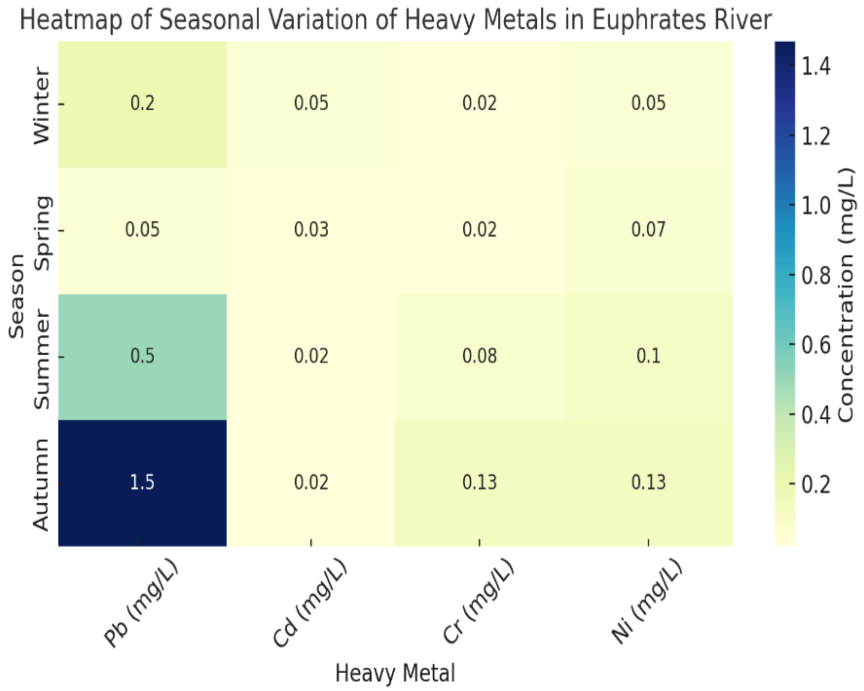

Figure 2. Seasonal variation in heavy metals (Pb, Cd, Cr, Ni).

Figure 3 depict the indicates seasonal variations in temperature, TDS, pH, DO, BOD_5, and total coliform bacteria. Temperature increased remarkably in summer (30 °C), while winter recorded the lowest reading. TDS was highest in winter (924 mg/L), reflecting low flow and high ionic status, whereas summer reflected dilution impacts. Dissolved oxygen decreased uniformly, reflecting least during autumn (4.91 mg/L), whereas BOD_5 recorded higher values during spring, reflecting increased organic inputs. Total coliform bacteria were maximum in winter (338 cfu/100 mL), which reflected high microbial pollution belonging to sewage outfall.

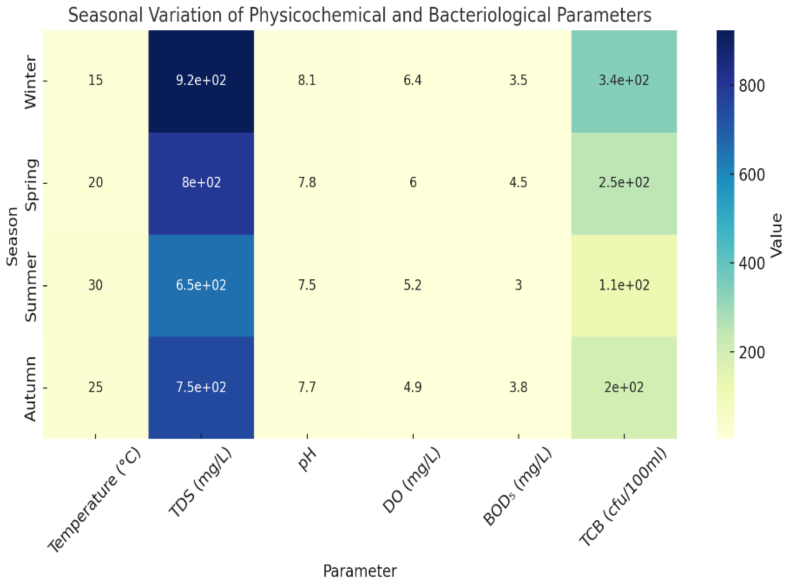

Figure 3. Heatmap of physicochemical and bacteriological parameters.

Figure 4 show the line graph visibly illustrates heavy metal variations throughout the four seasons. Lead increased sharply from spring to autumn, confirming its leadership as a pollutant in this segment of the river. Nickel and chromium showed medium increasing trends with the peak value in autumn, and cadmium was consistently low but slightly above safety levels. The graph illustrates that autumn season is the time of maximum contamination of most of the metals, likely due to agricultural runoff and wastewater discharge during periods of low river flow.

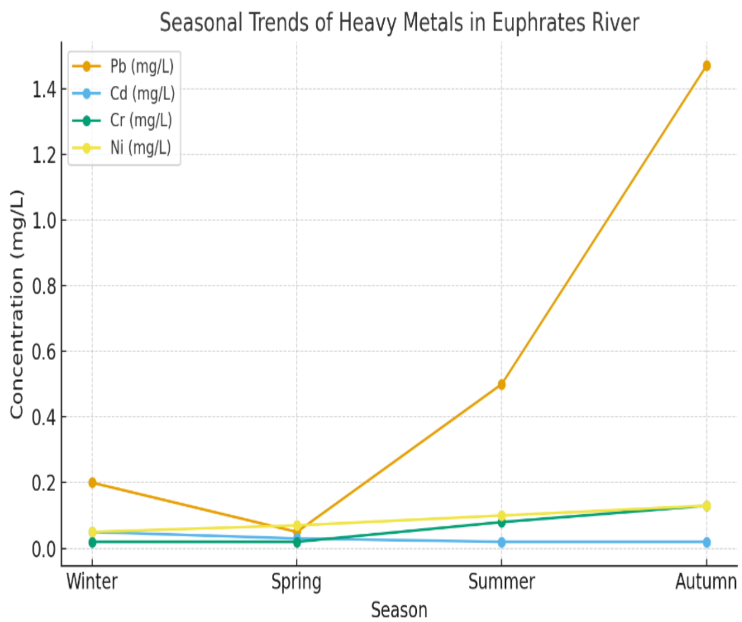

Figure 4. Seasonal trends of heavy metals.

Figure 5 show heatmap dendrogram how physicochemical parameters group based on season-to-season similarity. Dissolved solids were high and represented by TDS and TCB, which formed a close cluster, indicating that high dissolved solids are correlated with high bacterial growth. pH and DO group separately since they fluctuated separately, while temperature was close to DO because of the inverse relationship between them. This grouping supports multivariate interaction among parameters and also identifies key drivers of water quality variation across seasons.

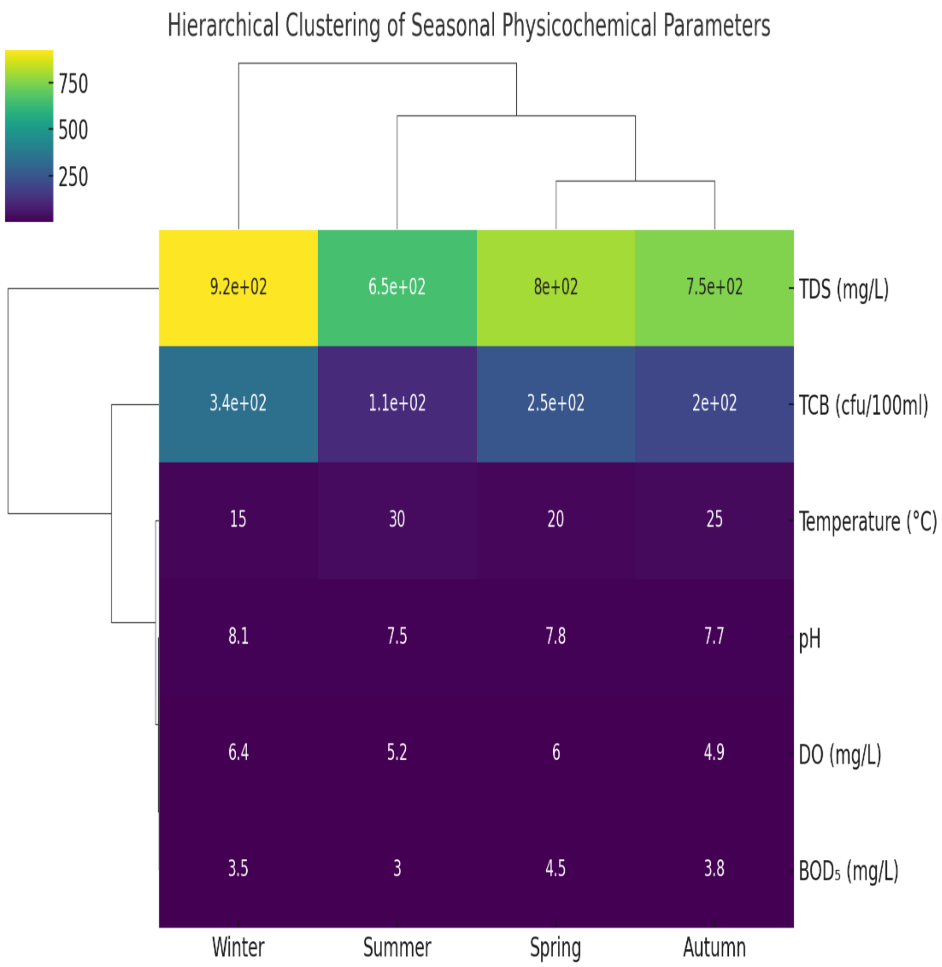

Figure 5. Hierarchical Clustering of Seasonal Physicochemical Parameters.

The above correlation matrix shows the direction and magnitude of association among water quality parameters. Strong negative correlation between temperature and dissolved oxygen (r = -0.87) confirmed that increases in temperature are responsible for reducing oxygen solubility. Positive correlation between TDS and TCB (r = 0.99) confirms that areas with higher dissolved solids promote microbial growth. There were also moderate correlations between BOD_5 and coliform counts that approximated the contribution of organic pollution towards sustaining bacterial activity. The diagram shows how chemical and physical processes combined contribute to microbial contamination of the river.

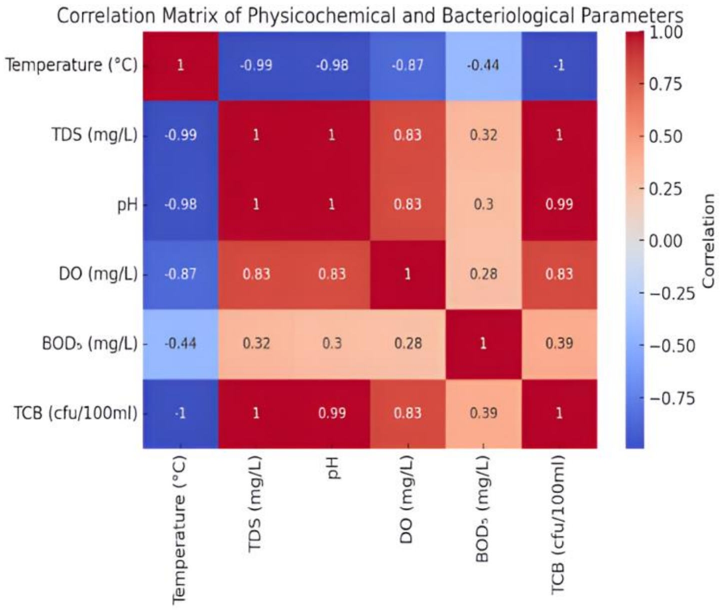

Figure 6. Physicochemical and bacteriological parameter correlation matrix.

Regression analysis showed a simple negative relationship of water temperature and dissolved oxygen. Regression line fit (DO = –0.07 × Temp + 7.33) shows that as the temperature increases, the quantity of dissolved oxygen in water decreases. This discovery confirms the thermodynamic nature of oxygen solubility and explains how the minimum DO values were recorded in autumn and summer samples. Reduced oxygen levels during warmer seasons impose more ecological stress on aquatic organisms.

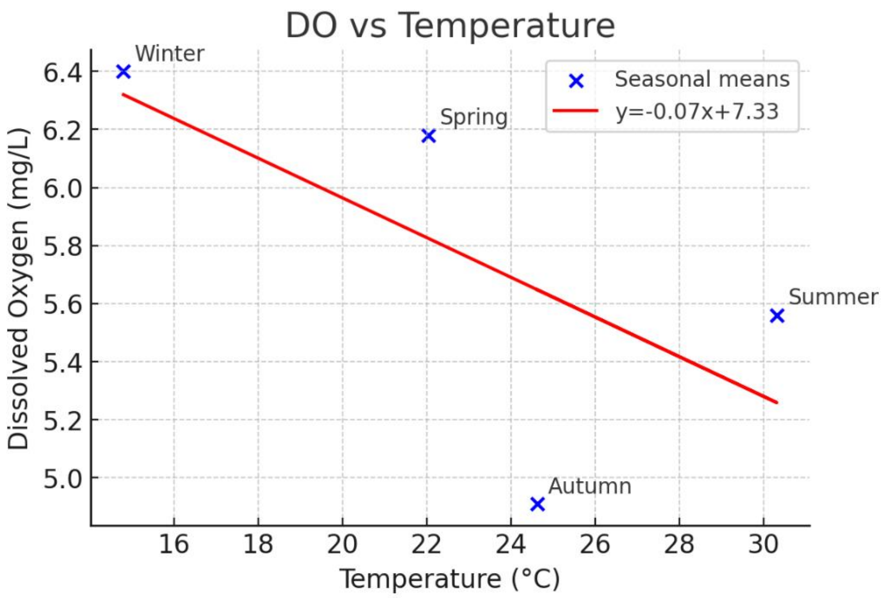

Figure 7. DO vs Temperature

There was a positive relationship between total dissolved solids and total coliform bacteria. The regression line (log10(TCB+1) = 0.00 × TDS + 1.07) indicates that rise in dissolved solids is correlated with rising bacterial numbers. This means that seasons and environments of higher ionic concentrations also support good environments for microbials to thrive, which are largely influenced by domestic wastewater, sewage discharge, and crop runoff into the river system.

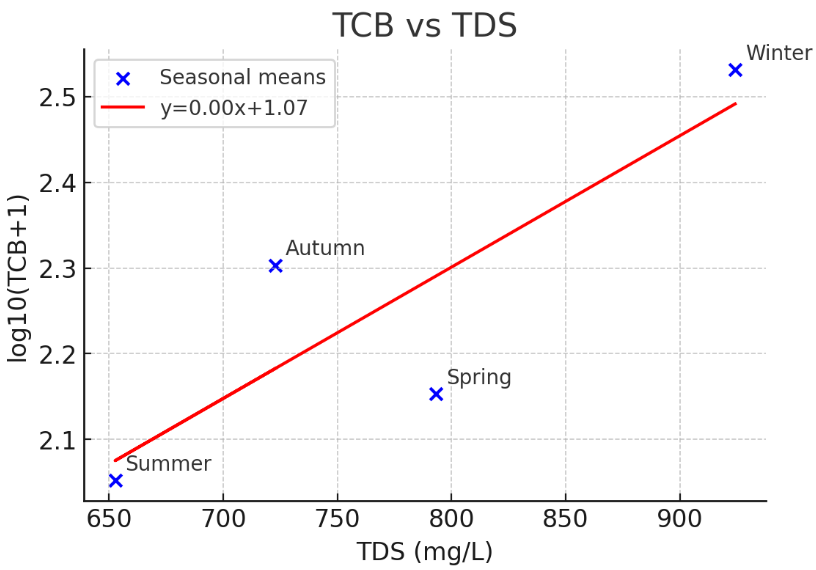

Figure 8. TCB vs TDS.

Pb values increased with rising TDS values, though seasonally variable. Autumn had the highest Pb reading far in excess of international safety limits, while spring and summer readings were quite low. The regression model supports the explanation that heavy metals and dissolved solids have similar sources of pollution such as untreated effluents and reduced dilution under low-flow conditions.

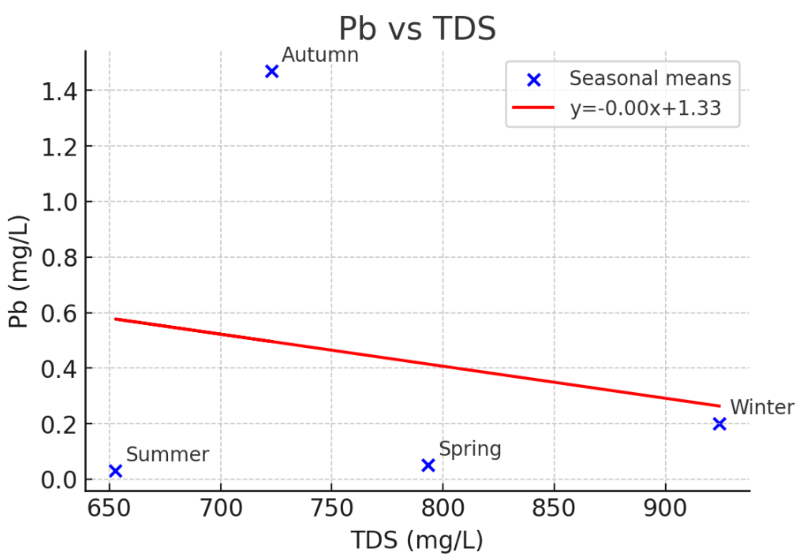

Figure 9. Pb vs TDS.

SUMMARY AND CONCLUSION

This research work investigated seasonal fluctuations of physicochemical properties, heavy metals, and bacteriological pollution in the Euphrates River at Najaf, Iraq, over a complete hydrological year. The results confirmed clear-cut seasonal patterns, demonstrating how climatic variation and human activities interact to affect water quality in this essential freshwater network.

Temperature registered its lowest readings in winter and highest in summer, and dissolved oxygen the opposite. Regression analysis confirmed this correlation by demonstrating that oxygen availability systematically decreases with rising temperature, thereby confirming the thermodynamic reaction of oxygen solubility. This seasonal loss of oxygen is a serious environmental concern for warmer seasons.

Total dissolved solids continued to hold consistently high values, especially in the winter season, and exceeded global aesthetic standards. The TDS regression model against total coliform bacteria confirmed that areas with high dissolved solids also had higher microbial contamination, consistent with the impact of sewage and runoff as major sources of pollution. Similarly, the Pb and TDS regression indicated that heavy metals rise with rising ionic content, autumn reporting maximum levels of contamination far exceeding WHO and USEPA guidelines.

These findings highlight that both chemical and bio contaminants occur together due to common anthropogenic sources such as untreated effluents and industrial discharges. Seasonal peaks of heavy metals in autumn and microbial contamination in winter also highlight the importance of time-based monitoring and control.

Environmentally, the cumulated stress of low oxygen, microbial contamination, and poisonous metals threatens biodiversity and the environmental balance of the river. Socio-economically, the dangerous quality of water threatens agriculture, domestic consumption, and public health in Najaf and its nearby surroundings.

The study identifies the urgent need for upgrading wastewater treatment plants, increased regulation of industrial effluent, and seasonal adjustment monitoring programs to consider variability between seasons. The integration of regression modelling with seasonality provides an improved quantitative understanding of the interaction among key parameters and facilitates informed evidence-based water resource management decision-making. Future studies must extend monitoring periods, expand spatial coverage, and integrate state-of-the-art molecular and predictive modelling techniques to better characterize pollution patterns and forecast threats.

AUTHOR CONTRIBUTIONS

Data curation, K.A.Z. and M.J.A.; Formal analysis, K.A.Z. and M.J.A.; Funding acquisition, M.J.A.; Investigation, K.A.Z. and M.J.A.; Methodology, K.A.Z. and M.J.A.; Project administration, M.J.A.; Resources, K.A.Z. and M.J.A.; Software, K.A.Z.; Visualization, K.A.Z.; Writing-original draft preparation, K.A.Z.; Writing-review & editing, K.A.Z. and M.J.A.; Supervision, M.J.A. All authors have read and agreed to the published version of the manuscript.

ACKNOWLEDGMENT

The authors would like to thank the University of Kufa, Faculty of Sciences, the Department of Ecology and Pollution, for providing the necessary facilities for their work on this project.

CONFLICT OF INTERESTS

No potential competing interest was reported by the authors.

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