MJFAS
Malaysian Journal of Fundamental and Applied Sciences

RESEARCH ARTICLE

Application of Chemometric Analysis for Water Quality Assessment in Bukit Goh, Kuantan

Wan Marlin Rohalin[a], Noorjima Abd Wahab[a*], Nadzifah Yaakub[b], Fazleen Abdul Fatah[c]

[a]Faculty of Applied Social Science, University Sultan Zainal Abidin, Gong Badak Campus, 21300 Kuala Nerus, Terengganu, Malaysia; [b]School of Animal Science, Aquatic Science and Environment, Faculty Bioresources and Food Industry, Universiti Sultan Zainal Abidin, Kampus Besut, 22200 Besut, Terengganu, Malaysia; [c]Faculty of Plantation and Agrotechnology, Universiti Teknologi MARA (UiTM), Campus Jasin, 77300 Merlimau, Melaka, Malaysia

Abstract The disturbance of rivers can significantly reduce water quality, ecosystem health, and environmental safety. This study assesses water quality and heavy metal contamination in the Bukit Goh region of Kuantan. Water samples were collected from Sungai Kuantan, Sungai Riau, and Sungai Pinang for physicochemical analysis, both on-site and in the laboratory. The Water Quality Index (WQI) classified pollution levels, revealing that Sungai Kuantan was slightly polluted (Class II), while Sungai Riau and Sungai Pinang were heavily polluted (Class III). Heavy metal analysis showed iron (Fe) at 67 ppb and aluminum (Al) at 2.36 ppb as the highest concentrations, followed by zinc (Zn) at 0.14 ppb and others at lower levels. Principal Component Analysis (PCA) and Agglomerative Hierarchical Clustering (AHC) indicated strong correlations among various parameters, such as turbidity with total suspended solids (TSS) and biochemical oxygen demand (BOD) with ammonia nitrogen (NH_3-N). Temperature also had positive links to chemical oxygen demand (COD) and heavy metals, indicating seasonal variations in pollution. These findings underscore the urgent need for improved water management and effective pollution control strategies to safeguard aquatic ecosystems and public health.

Keywords: Water Quality, Principal Component Analysis (PCA, Agglomerative Hierarchical Clustering (AHC), risk assessment.

Introduction

Water is one of the most vital resources on Earth, playing a crucial role in sustaining life, supporting ecosystems, and driving economic activities [1]. Despite its importance, water resources are increasingly threatened by pollution, climate change, and over-extraction [2]. Among the most affected water bodies are rivers, which serve as primary sources of freshwater for drinking, agriculture, and industry. The contamination of rivers due to human activities has become a pressing global issue, requiring advanced analytical techniques for effective monitoring and management.

Rivers are highly susceptible to pollution from various sources, including industrial discharge, agricultural runoff, and domestic waste [3]. Heavy metals, pesticides, microplastics, and excessive nutrients degrade water quality, posing significant risks to aquatic ecosystems and human health. Conventional water quality assessments often fall short in identifying pollution sources and understanding complex water chemistry interactions. One prominent example of water pollution on an international scale is the pollution of the Ganges River in India. This sacred river is heavily polluted due to untreated sewage, industrial waste, and religious offerings that contribute to the degradation of water quality. Estimates suggest that approximately 1.3 billion liters of untreated sewage is discharged into the river each day, leading to severe health risks for local populations, including waterborne diseases like cholera and dysentery [4].

***For correspondence:**
noorjima@unisza.edu.my

Received: 05 April 2025
Accepted: 7 August 2025

Another example is the contamination of the Great Lakes in North America, which are some of the largest freshwater bodies in the world. They have faced significant pollution from agricultural runoff, industrial discharges, and urban pollution, resulting in harmful algal blooms that threaten ecosystems and public health [5]. These cases illustrate the urgent need for global collaboration and stronger regulations to address water pollution effectively and protect vital water resources.

In Malaysia, water pollution is a pressing concern that has been exacerbated by rapid industrialization, urbanization, and agricultural practices. Major rivers, such as the Klang and Gombak, face significant pollution challenges due to the discharge of untreated wastewater, waste oil, and debris from surrounding development [6, 7]. Additionally, the use of fertilizers and pesticides in agriculture often leads to runoff that contaminates nearby waterways. This situation not only impacts local biodiversity but also affects the livelihoods of communities dependent on clean water for fishing and agriculture. To tackle these challenges, Malaysia is taking steps to enhance water quality management and promote sustainable practices, but continued efforts and public awareness are essential for meaningful change.

To address this, chemometric analysis tools have been increasingly employed to interpret large datasets and provide meaningful insights into river pollution dynamics [8, 9]. Chemometric techniques such as Principal Component Analysis (PCA) and Hierarchical Cluster Analysis (HCA), are powerful statistical tools used to assess water quality patterns, identify pollution sources, and model environmental factors influencing river contamination [10].

A study conducted on the Muda River Basin, Malaysia, employed chemometric tools to evaluate water quality and identify pollution sources [11]. PCA results revealed that heavy metal contamination was strongly associated with industrial discharge, while nutrient enrichment was linked to agricultural activities. AHC further classified river sections based on pollution intensity, highlighting critical zones requiring immediate intervention.

The integration of chemometric analysis in river pollution studies enhances our ability to monitor, interpret, and manage water quality effectively. By identifying pollution sources and assessing trends, these tools support evidence-based decision-making for conservation efforts and regulatory policies. Moving forward, the application of chemometric techniques should be expanded to other river systems to ensure sustainable water resource management and environmental protection.

Materials and Methods

Study Area

The study was conducted near the bauxite deposit site in Bukit Goh, Kuantan, Pahang, focusing on three rivers: Sungai Kuantan, Sungai Riau, and Sungai Pinang. These rivers were chosen as sampling sites due to their proximity to the mining activities, ranging from 0.5 to 4 km, making them likely to be affected by pollution. The selection was also based on previous data and past pollution incidents reported by the Department of Environment, Kuantan. The coordinates for all sampling points were recorded using a GPS during fieldwork.

Sample Collection

Water sampling was colected, following the comprehensive guidelines set forth by the [12] for collection, containment, and preservation. Samples were meticulously gathered from three distinct rivers: Sungai Kuantan, with its meandering banks; Sungai Riau, known for its lush surroundings; and Sungai Pinang, characterized by its vibrant ecosystem. At each river site, five sampling points were established to ensure a thorough representation of water quality. Sampling efforts were conducted in the early morning at 9 AM and again in the evening at 5 PM, quarterly over a two-year period from 2018 to 2020, capturing the dynamic seasonal variations inherent in the region.

Samples were manually extracted from a depth of 0.5 meters using a specialized horizontal water sampler, ensuring a representative sample from just below the surface. Sampling at 0.5 m was chosen as it reflects the surface layer commonly used for drinking water intake and treatment. To maintain sample integrity, they were stored in high-quality 0.5-liter polyethylene bottles.

For Biochemical Oxygen Demand (BOD) analysis, 250 mL BOD bottles were filled, carefully capped underwater to prevent contamination, wrapped in light-blocking aluminum foil, and stored in a dark box to protect them from light exposure. To preserve the quality of samples intended for BOD and heavy metal analysis, we acidified them with 69% nitric acid, adjusting the pH to approximately 2.

All samples were then stored in a temperature-controlled environment at around 4°C in a cooler box, effectively inhibiting any microbial activity that could compromise results [12].

Water Quality Assessement

For real-time water quality assessment, we employed the advanced YSI Professional Plus Handheld Multiparameter instrument, which allowed us to accurately measure vital parameters such as temperature, pH, dissolved oxygen (DO), total suspended solids (TSS), and ammoniacal nitrogen (NH3-N), representing the nitrogen content of ammonia. The water's turbidity—a key indicator of sediment and particulate matter, was measured using a Portable Turbidimeter (2100 Q HACH). Prior to each sampling session, we meticulously calibrated every instrument to ensure data accuracy, and we took measurements three times at each station to enhance reliability and consistency.

Following the collection phase, laboratory analyses were conducted meticulously according to APHA (2017) methods. The ultrapure water (Milli-Q) was used for reagent and blank preparations, ensuring that no contaminants influenced our results. Both field blanks and reagent blanks were prepared and analyzed concurrently with the water samples. The parameters analyzed included BOD, Chemical Oxygen Demand (COD), and TSS, with strict adherence to standard holding times to ensure the validity of the test results. The specific instruments and methods employed in this analysis are detailed in Table 1.

Table 1. Instrument and method used for water quality parameters analysis [12]

Parameter	Instrument used
Dissolved oxygen (DO)	YSI Professional Plus Handheld Multiparameter 449D.
pH	YSI Professional Plus Handheld Multiparameter 449D.
Ammoniacal- nitrogen (NH_3-N)	YSI Professional Plus Handheld Multiparameter 449D.
Turbidity	Portable Turbidimeter (2100 Q HACH)
Biochemical oxygen demand (BOD)	-
Chemical Oxygen Demand (COD)	Digital Reactor Block (HACH DRB 200) and Colorimeter (DR2800 HACH)
Total Suspended Solids (TSS)	-
Heavy metals	ICP-MS

Quality control is important for the field and analytical works to ensure that highly representative results. All sample preparation and preservations conducted followed the standard procedures [12]. Standard Reference Material (SRM) (1640a), National Institute of Standards and Technology (NIST)) was used to evaluate the method used in the determination of heavy metals in natural water. The certified values for elements in SRM 1640a were measured by the Inductive Coupled Plasma-Mass Spectrometry (ICP-MS) and compared to the certified reference material CRM 1640a for validation as shown in Table 2. The recovery percentages were between 88.0% to 96.0%.

Table 2. Concentrations of metals found in Standard Reference Material SRM1604a (Natural water) from the National Institute of Standards and Technology (NIST)

Heavy Metal	Certified Value (ppb)	Measured Value (µg/L)	Recovery (%)
Al	14.45	13.87	96.0
Fe	26.77	24.98	93.3
Zn	12.69	11.28	88.9
Cd	0.27	0.24	88.9
Ni	2.58	2.37	91.9
Pb	0.38	0.35	92.1
Cu	7.77	6.95	89.4
As	4.18	3.88	92.8

Water Quality Index (WQI)

The Water Quality Index (WQI) was thoroughly assessed using the Department of Environment (DOE) WQI standards, integrating six critical parameters: dissolved oxygen (DO), BOD, COD, ammoniacal nitrogen, suspended solids, and pH. The WQI formula [13] was applied rigorously to categorize the overall water quality, offering a clear and comprehensive representation of the ecological status of the waterways studied. This index serves as an essential tool for stakeholders to understand water quality dynamics and address potential environmental concerns effectively.

Heavy Metals Analysis in Water Samples

Water samples for heavy metal analysis were preserved with a few drops of high-purity nitric acid and filtered through 0.45 µm Whatman microfiber filter paper to remove suspended particles. The filtered samples were then placed in auto-sampler vials for direct injection into the ICP-MS. Heavy metal concentrations were measured using the Perkin Elmer ELAN 9000 ICP-MS, with results expressed in micrograms per liter (ppb). Prior to analysis, the ICP-MS underwent sensitivity checks, detection limit identification, and calibration, following EPA 6020A guidelines. The instrument required at least 30 minutes to reach thermal stability before calibration. Standard solutions were prepared to ensure accurate data.

Data Analysis

Principal Component Analysis (PCA)

A PCA correlation analysis was employed to evaluate the strength of the relationships among water quality parameters and the selected heavy metals variables. The results of PCA are considered to be significant when the eigenvalue of a principal component is greater than one. Prior to PCA, Kaiser-Meyer-Olkin (KMO) and Barlett's tests were implemented at the beginning of the analysis to determine the suitability of data for the PCA as well as to evaluate the adequacy of the data. The KMO test results should be greater than 0.5 and Barlett's test p-value must be significant at a 0.05 level

Agglomerative Hierarchical Cluster Analysis (AHC)

In this study, an AHC was carried out to group sampling stations in the Sungai Kuantan, Sungai Riau, and Sungai Pinang based on their pollution level classifications in water, using Squared Euclidean Distances and Ward's Method. The resulting clusters are presented visually as dendrograms, which provide an overview of the clustering structure.

Data Treatment

For water quality parameters or heavy metals concentration with values below the method detection limit (MDL), a substitution method was applied by assigning a value equal to half the MDL (i.e., 0.0005 mg/L). This approach is widely adopted in environmental research to minimize bias in statistical analyses, particularly when dealing with non-normally distributed data [32].

Results and Discussion

Water Quality Assessment

In this study, water samples were collected from three sampling stations: Sungai Kuantan, Sungai Pinang, and Sungai Riau, during both the dry and wet seasons from 2018 to 2020. The Water Quality Index (WQI) was calculated based on six key parameters: pH, Dissolved Oxygen (DO), Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), Total Suspended Solids (TSS), and Ammonia Nitrogen (NH_3-N). The sub-indices for these parameters and the WQI values for the three rivers are summarized in Table 3.

The pH values in Sungai Kuantan ranged from 5.456 to 6.23, indicating an acidic environment (Class II-III, NWQS). This is consistent with previous studies [14]. Low pH can increase heavy metal solubility, harming aquatic life. The acidity may result from pollutants like agricultural runoff, industrial waste, or sewage. In contrast, rivers like Sungai Sedim, Sungai Bertam, and Sungai Selangor recorded pH levels within the normal range (6.15–7.24), likely due to lower pollution levels and regular monitoring [15, 16]. However, the statistical analysis using ANOVA showed that there is no significant difference in pH among the sampling stations and between the dry and wet seasons ($p > 0.05$).

The Biochemical Oxygen Demand (BOD) values for Sungai Kuantan, Sungai Riau, and Sungai Pinang in the dry season were 1.23 ± 0.6 mg/L, 0.825 ± 0.37 mg/L, and 1.03 ± 0.47 mg/L, respectively. In the wet season, the BOD values were 1.328 ± 0.73 mg/L, 1.102 ± 0.21 mg/L, and 1.048 ± 0.27 mg/L. Statistical analysis by applying ANOVA showed that there was no significant difference in BOD levels among sampling locations and season variation ($p > 0.05$). In addition, the results from the Table 1 showed that BOD levels were slightly higher in the dry season, likely due to reduced river flow that limits dilution and causes organic pollutants to accumulate, increasing microbial activity and oxygen demand.

DO levels ranged from 2.4 to 5.3 mg/L in the dry season and 3.2 to 5.2 mg/L in the wet season, classifying the rivers under Class II (NWQS). There were statistically significant differences in DO levels between sampling stations ($p = 0.003$). Post-hoc analysis revealed that Sungai Kuantan differed significantly from Sungai Pinang and Sungai Riau. Higher DO levels during the wet season align with [17], attributed to increased mixing from higher river discharge. A decreasing trend in DO levels from 2016 to 2020 suggests declining water quality [14, 18, 19]. Lower DO in Sungai Pinang may result from stagnant water and effluent accumulation, while warmer temperatures during the dry season reduce oxygen solubility (Omer, 2019). Other rivers, like Sungai Jertih and Sungai Petani, showed higher DO levels (6.30–10.09 mg/L), influenced by local conditions [20, 21].

Turbidity ranged from 10.9 to 43.1 NTU (dry season) and 5.5 to 40.2 NTU (wet season), classified as Class I (NWQS). Unlike typical trends, turbidity was slightly higher in the dry season, likely due to anthropogenic activities and effluent discharge. Runoff from bauxite mining, agriculture, and urban areas contributes to turbidity [22]. Previous studies reported similar turbidity levels [14] or lower levels [18]. In comparison, Sungai Pusu and Sungai Balok had significantly higher turbidity, influenced by erosion and heavy rainfall. [22, 23] The results showed that there was no significant difference in turbidity between the dry and wet seasons, but were found significantly difference between different sampling locations, as indicated by a p-value of 0.046 ($p < 0.05$).

The COD values in the dry season were as follows: Sungai Kuantan (43.03 ± 0.53 mg/L), Sungai Riau (40.36 ± 5.86 mg/L), and Sungai Pinang (39.835 ± 2.83 mg/L). In the wet season, the COD values were Sungai Kuantan (33.682 ± 7.16 mg/L), Sungai Riau (33.48 ± 8.10 mg/L), and Sungai Pinang (35.682 ± 6.14 mg/L). COD levels in this study were found to be within the range of 39.8 to 43.03 mg/L during the dry season and 28.8 to 33.6 mg/L during the wet season. These values are slightly higher than the permissible limit standard of the National Water Quality Standards (NWQS) of 5-50 mg/L and were classified as Class III. The maximum COD levels were recorded during the dry season, as dry weather reduces river velocity, which is necessary to transport organic material from upstream to downstream. Higher COD concentrations during the dry season may also be linked to rising temperatures, higher biological activity, and an increased rate of organic matter decomposition [24]. The COD of the water between the sampling locations and season was found to be not significantly different ($p > 0.05$). The presence of COD in river basins is often attributed to anthropogenic activities, such as industrial waste discharge [25]. The COD values suggest that the water had a high organic content, indicating a decline in water quality. Previous studies recorded COD levels ranging from 1-79 mg/L, which is higher than the present study [18], while [19] reported COD values of Sungai Kuantan at 11.5 mg/L.

The TSS levels in the dry season were 23.12 ± 6.98 mg/L for Sungai Kuantan, 28.34 ± 5.24 mg/L for Sungai Riau, and 26.14 ± 4.72 mg/L for Sungai Pinang. During the wet season, the TSS values were 20.85 ± 4.31 mg/L, 24.62 ± 5.12 mg/L, and 21.92 ± 3.97 mg/L, respectively. ANOVA analysis showed a significant difference in TSS values among the sampling stations ($p = 0.02$) but not significantly difference between seasons. TSS levels ranged from 9.8 to 40.2 mg/L during the dry season and 17.8 to 42.6 mg/L during the wet season. The highest mean TSS values were recorded in Sungai Kuantan during the wet season. Based on NWQS classifications, all stations were classified as Class III. The maximum threshold limit of TSS for rivers that support aquatic life is 150 mg/L. The findings of this study are in agreement with past studies, which also recorded peak TSS concentrations during the wet season in rivers on Peninsular Malaysia's east coast [18].

A previous study in Kuantan showed TSS values ranging from 20.74 to 52.46 mg/L, with the highest being recorded at Sungai Balok and the lowest at Sungai Karang [18]. In Malaysia, high TSS levels in rivers are commonly recorded during the wet season due to runoff from logging, agriculture, and urban areas [13]. Suspended solids indicate the presence of impurities such as soil, industrial waste, and organic matter, including dead plants, living organisms, and sewage [26]. Excessively high or low TSS concentrations can affect wastewater treatment efficiency, water clarity, and irrigated crops [27]. TSS levels contribute to turbidity, reducing light penetration and limiting photosynthetic activity, which in turn affects aquatic life. Additionally, high TSS can serve as a nutrient source for bacteria, further degrading water quality.

The Ammonia Nitrogen (NH3-N) values in the dry season were 0.72 ± 0.68 mg/L for Sungai Kuantan, 0.455 ± 0.44 mg/L for Sungai Riau, and 0.525 ± 0.50 mg/L for Sungai Pinang. In the wet season, the NH3-N levels were 1.068 ± 0.27 mg/L, 0.714 ± 0.18 mg/L, and 0.596 ± 0.19 mg/L, respectively. Statistical analysis showed no significant difference in NH3-N levels among sampling locations and seasons ($p > 0.05$). NH_3-N levels tend to be slightly elevated during the wet season as rainfall enhances leaching and mobilization of nitrogen compounds from surrounding soils, fertilizers, and waste deposits into the river systems.

Table 3. Seasonal variation of mean ± SD water quality parameters (ppm dry weight) in water samples of Sungai Kuantan, Sungai Riau, and Sungai Pinang

	Sungai Kuantan		Sungai Riau		Sungai Pinang	
Season	**Dry**	**Wet**	**Dry**	**Wet**	**Dry**	**Wet**
pH	6.23±0.5	6.12±0.31	5.69±0.63	5.45±0.36	6.21±0.62	5.94±0.28
BOD (mg/L)	1.23±0.6	1.32±0.7	0.82±0.37	1.10±0.21	1.03±0.4	1.04±0.27
COD (mg/L)	43.0±0.1	33.68±7.1	40.36±5.8	33.48±8.1	39.83±2.8	28.83±9.2
DO (mg/L)	5.3±0.29	5.582±0.4	2.71±0.09	3.548±0.7	2.475±0.4	3.284±0.9
TSS (mg/L)	40.2±0.7	47.67±7.5	11.72±3.5	17.81±2.0	9.835±3.2	26.65±9.3
Turbidity (NTU)	43.1±3.2	40.25±4.8	14.79±3.7	11.68±1.1	15.53±4.1	10.99±0.5
NH_3N(mg/L)	0.72±0.6	1.068±0.2	0.45±0.44	0.71±0.18	0.525±0.5	0.596±0.19

Water Quality Index (WQI)

Table 4 show the WQI values for Sungai Kuantan in the dry and wet seasons were 80.096 and 78.119, classifying it as Class II, meaning the river was clean but required standard treatment for water supply. n Sungai Riau and Sungai Pinang had WQI values of 71.53 and 72.56 in the dry season and 71.54 and 74.02 in the wet season, respectively, classifying them as Class III. This classification indicates that these rivers were slightly polluted and required conventional treatment before use for water supply or fisheries. According to the DOE-WQI classification, Sungai Kuantan was categorized as Class II, whereas Sungai Pinang and Sungai Riau, located downstream with high anthropogenic activities, were classified as Class III, indicating slight pollution. This was mainly due to very low DO concentrations at these stations. Despite Sungai Riau being located upstream, its proximity to Bukit Goh, where mining activities take place, contributed to pollution. This is consistent with the Environmental Quality Report (2014), which reported WQI values of 88 for Sungai Kuantan and 77 for Sungai Riau.

WQI values generally decreased from upstream to downstream along the rivers, which was expected based on individual water quality parameters. The present study recorded WQI values ranging from 71 to 80 for Sungai Kuantan, Riau River, and Pinang River. In comparison, a study by [14] reported WQI values for Sungai Kuantan and its tributaries between 86 and 95. Additionally, Sungai Riau was previously reported to be polluted by heavy metals due to bauxite mining in Bukit Goh [28].

Table 4. Sub-indexes of six water quality parameters and Water Quality Index (WQI)for different water sampling stations

River	Season	Si DO	Si BOD	Si COD	Si AN	Si TSS	Si pH	WQI	Class
Sungai Kuantan	Dry	75.85	95.19	54.01	70.72	76.50	92.20	80.09	II
	Wet	76.85	94.78	60.85	56.72	73.58	87.90	78.11	II
Sungai Riau	Dry	28.32	96.91	54.74	80.54	90.74	76.88	71.53	III
	Wet	41.75	95.738	61.17	68.14	87.4	67.75	71.54	III
Sungai Pinang	Dry	24.12	96.04	56.	77.6	91.79	91.29	72.58	III
	Wet	36.11	95.96	65.78	74.2	83.5	85.41	74.02	III

Fe, Al, and Pb levels in Water Samples

Table 5 shows the Fe levels recorded during both the dry and wet seasons at three distinct sampling locations. The concentration of Fe in the water was the highest among all tested metals across all rivers. The most notable concentration was found in Sungai Riau at 3.439 ± 0.0010 ppb, followed by Sungai Pinang at 0.477 ± 0.003 ppb and Sungai Kuantan at 0.2 ± 0.001 ppb. During the wet season, Fe concentrations rose significantly, with Sungai Riau measuring 275.740 ± 0.12 ppb, Sungai Kuantan at 113.497 ± 0.13 ppb, and Sungai Pinang at 14.711 ± 0.007 ppb. The Fe concentrations in the studied rivers were generally low, remaining well below the permissible limit of 1.0 ppm [13]. Seasonal variations showed lower Fe levels during the dry season due to reduced runoff and sediment transport, whereas higher concentrations were observed in the wet season, reaching up to 275.7 ppb at Sungai Riau. This increase is linked to higher water flow and increased erosion. Despite these fluctuations, Fe levels in the rivers were within acceptable limits, indicating no immediate concern for water quality. However, continuous monitoring is necessary to detect any potential changes that could impact aquatic life and human health. Fe is an essential micronutrient however, excessive exposure will lead to health risks, including anemia, liver damage, and increased cancer risk. In aquatic systems, Fe tends to accumulate in biota rather than remain dissolved in water [45].

The concentration of Al in the water samples during the dry season are 0.073 ± 0.001 ppb, 0.582 ± 0.001 ppb, and 0.072 ± 0.001 ppb, and 28.702 ± 0.03 ppb, 30.047 ± 0.01 ppb, and 25.810 ± 0.01 ppb during the wet seasons respectively. According to the Kruskal-Wallis statistical analysis, there were no significant variations in Al concentrations among sampling stations ($p > 0.05$), but a significant difference was observed between the dry and wet seasons. Al concentrations ranged from 0.072 to 30.04 ppb, with higher levels recorded during the wet season. These values were significantly lower than the permissible limit of 60 ppb [13] and far below the WHO and USEPA standard of 2000 ppb. Comparisons with previous studies in Kuantan rivers showed that past contamination, particularly during bauxite mining activities, led to much higher Al levels. Although Al is naturally abundant, excessive concentrations can be toxic to aquatic organisms, particularly those with gills [29]. Once absorbed, it tends to accumulate in living tissues faster than it can be metabolized or excreted. In humans, prolonged exposure to Al has been linked to neurological disorders, reduced cognitive function, and a higher risk of Alzheimer's disease [30]. Ingesting high levels of Al may also interfere with phosphate absorption, which is essential for bone development, leading to bone diseases, especially in children [31]. Given its potential toxicity, regular monitoring is essential to prevent future contamination risks.

Moreover, the highest level of Pb during the wet season was found in Sungai Riau (0.591 ppb), while the lowest was recorded in Sungai Pinang (0.243 ppb). During the dry season, Pb levels in water samples from all three rivers were below 0.001 ppb and nearly undetectable, indicating a notable increase in concentration during the wet season. Pb was detected in three rivers at a very low concentration of 0.001 ppb, which is almost undetectable. The measured values were far below the permissible limits of 0.02–2 ppm [13] and 0.05 mg/L [33]. Previous studies reported higher Pb levels, likely influenced by factors such as pollution sources, geographic location, and seasonal changes. The current study suggests that Pb contamination in rivers is minimal. However, given its toxic nature and bioaccumulation risks, continuous assessment is recommended to ensure long-term water safety. Pb poses serious risks to both animals and humans. In animals, it affects physiological, behavioural, and biochemical functions [34]. Meanwhile, in humans, especially pregnant women, high Pb exposure can cause miscarriage, stillbirth, premature birth, and low birth weight. It may also reduce fertility, as Pb accumulates in bones and can later be released into the bloodstream [35].

Table 5 Mean heavy metals values (ppb) in the water surface among rivers

		Rivers		
Heavy metal (ppb)	**Seasons**	**Sungai Kuantan**	**Sungai Riau**	**Sungai Pinang**
Fe	Dry	0.2±0.001	3.439±0.001	0.477±0.003
	Wet	113.497±0.13	275.740±0.12	14.711±0.007
Al	Dry	0.073±0.001	0.582±0.001	0.072±0.001
	Wet	28.702±0.03	30.047±0.01	25.810±0.01
Pb	Dry	0.001±0.001	0.005±0.001	0.002±0.001
	Wet	0.335±0.001	0.591±0.001	0.243±0.001

Principal Component Analysis (PCA) and Agglomerative Hierarchical Clustering (AHC)

The correlation biplot analysis of water quality in three rivers in Figure 1 revealed certain correlations between different parameters. These correlation findings provide insights into the relationships between different water quality parameters and heavy metal concentrations. The correlation coefficient (r) ranges vary according to the parameters of each river. The KMO results for data in Sungai Kuantan, Sungai Riau and Sungai Pinang were 0.712, 0.771 and 0.740 respectively (greater than 0.5) and sufficient for PCA extraction.

The biplot from the Principal Component Analysis (PCA) for Sungai Kuantan explains 78.46% of the variation in water quality, with the first component (F1) contributing 44.74% and the second (F2) 33.71%. This indicates that these components are crucial for understanding the relationships among water quality parameters. Key findings include that NH3-N (ammonia), BOD (biochemical oxygen demand), and turbidity have strong positive values on F1, indicating they significantly influence water quality along this axis. Conversely, DO (dissolved oxygen), COD (chemical oxygen demand), TSS (total suspended solids), and pH have negative values on F1, suggesting an opposite trend. F2 is mainly influenced by Pb and Fe. The DO level in water samples of Sungai Kuantan showed a strong negative correlation with BOD (r = -0.905). This finding is consistent with a study conducted in the Terengganu River Basin, which also reported a negative correlation between DO and BOD, highlighting the common pattern where increased organic pollutants lead to lower dissolved oxygen levels [35]. DO level also exhibited a negative low correlation with ammonia (NH3-N) and turbidity (r = -0.361, -0.435), while having a positive moderate correlation with total suspended TSS, pH, COD, and temperature (r = 0.113 - 0.638). Consequently, elevated levels of NH3-N and turbidity in the water also contribute to oxygen depletion. The increases of the capacity of poisonous ammonia leads to low DO levels in the water, causing aquatic species vulnerable to stress [36]. The pH level demonstrated a significantly strong positive correlation with TSS (r = 0.912), NH3-N (r = 0.914), and BOD (r = 0.857), respectively. Moreover, COD exhibited a moderate positive correlation with all heavy metals examined in the water samples, including Pb, Al, and Fe (r = 0.303 - 0.75). In addition, all heavy metals showed significant positive correlations with each other within the range of r value between 0.88 to 0.99. This suggests that heavy metals likely came from the same source, such as metal and non-ferrous mineral deposits in the area. This also indicates that the observed variations in water quality and heavy metal concentrations may be influenced by bauxite mining activities in Kuantan, as supported by [37], who reported similar contamination trends near mining sites as bauxite mining plays a significant role in altering these parameters.

In addition, the PCA biplot for Sungai Riau illustrates the relationships between various water quality parameters along two principal components, F1 (39.52%) and F2 (30.65%), which together explain 70.16% of the total variance in the dataset. Parameters positioned closely together share strong positive correlations, while those on opposite sides exhibit negative correlations. Pb, turbidity, NH3-N, and BOD are positively associated with F1, indicating that they contribute significantly to variations along this axis. In contrast, DO, TSS, COD, and pH are negatively correlated with F1, suggesting an inverse relationship with the first group of parameters. Notably, DO and COD are strongly related, pointing in the same direction, implying they might be influenced by similar environmental factors. A previous study by [38] found that higher BOD and COD levels reduce DO in water bodies, as increased pollution raises oxygen demand. Bauxite mining worsens these problems by causing land clearing and runoff, which elevate organic matter and pollutants, further depleting oxygen in the rivers.

Meanwhile, the PCA results for Sungai Pinang also revealed that the three studied heavy metals and river COD had high loadings in the same factor group (F1) across all three rivers. A similar pattern was observed in previous study [39] where PCA showed COD loaded strongly with BOD on one factor, and heavy metals like Cu and Pb grouped on a related factor, suggesting that organic pollutants and metals often share common pollution sources, such as industrial or domestic waste discharge. However, others parameters were placed in a separate factor group (F2), suggesting no significant correlation between them with heavy metal concentrations. This implies that variations in parameters such as pH, NH3-N, TSS, and DO not strongly influence heavy metal levels. This result is in agreement with [40] that reported water quality parameters such as pH and DO may not always correlate strongly with heavy metal concentrations but it suggests that this factors still help distinguish areas affected by natural processes from those influenced by human activities. The highest percentage of variability was explained by D1, highlighting the greater contribution of heavy metals to overall water pollution. Overall, this PCA biplot identifies key water quality parameters and their interrelationships, which can help in monitoring pollution and managing water quality more effectively.

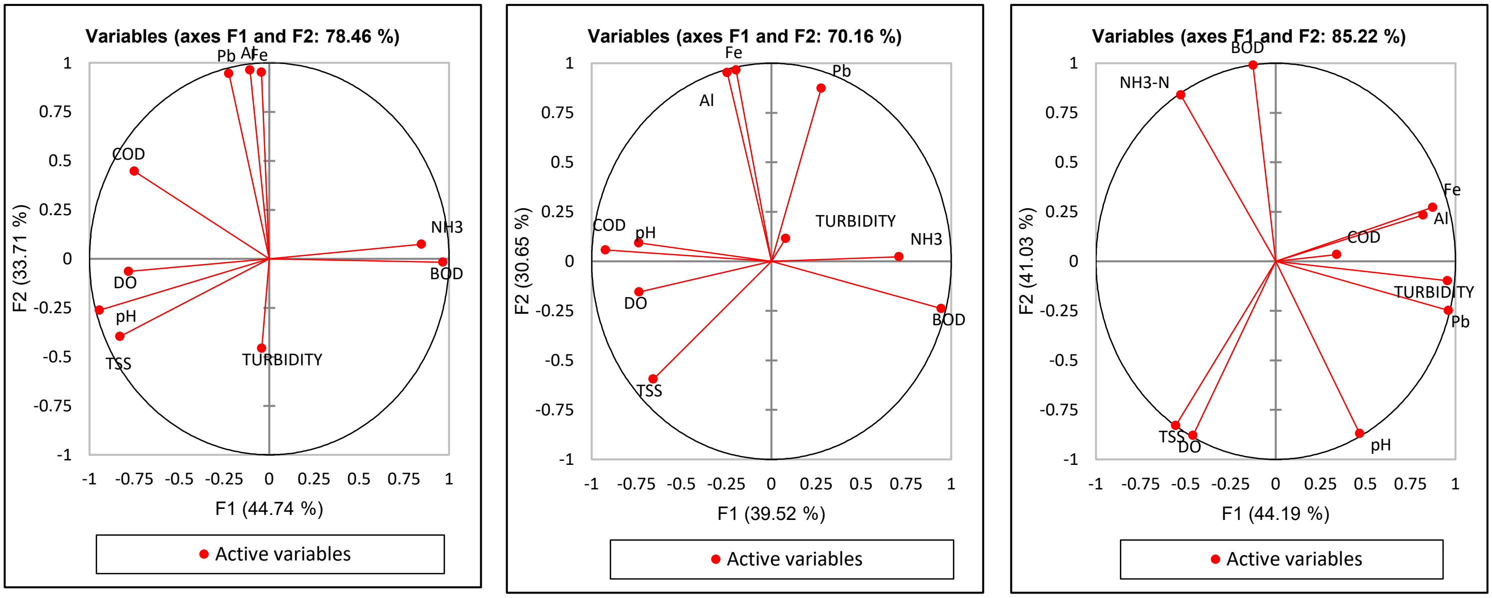

Figure 1. PCA biplot of water quality parameters (ppm dry weight) in water samples of a) Sungai Kuantan, b) Sungai Riau, and c) Sungai Pinang

Agglomerative Hierarchical Clustering (AHC) was performed using the Ward's linkage method, which minimizes the total within-cluster variance. The Euclidean distance metric was used to compute dissimilarities between samples. To validate the consistency of the resulting dendrogram, the cophenetic correlation coefficient (CCC) was calculated. A CCC value for Sungai Kuantan, Sungai Riau and Sungai Pinang were 0.797, 0.8165 and 0.6486 indicates a good fit between the dendrogram structure and the original distance matrix.

Cluster analysis was performed to classify water quality parameters and heavy metals based on their similarities and dissimilarities. The results revealed distinct clustering patterns in different river systems, as represented by dendrograms in Figures 2. The dendrogram illustrates the hierarchical clustering of water quality parameters based on their similarity, with the y-axis representing dissimilarity levels. Parameters that merge at lower dissimilarity values share stronger relationships, while those connected at higher levels are more distinct.

In Sungai Kuantan, three main clusters are identified which are the first cluster (turbidity, BOD, NH3-N) indicates a strong association, likely related to organic pollution. The second cluster (Al, Pb, Fe) suggests a link between metal contaminants, while the third cluster (COD, DO, pH, TSS) represents parameters influencing water chemistry. The blue cluster, merging at the highest dissimilarity level (~20), is the most distinct, while the red and green clusters are moderately related, merging around a dissimilarity level of 10. This clustering pattern highlights potential pollution sources and interactions among water quality parameters, providing insights into the underlying environmental processes.

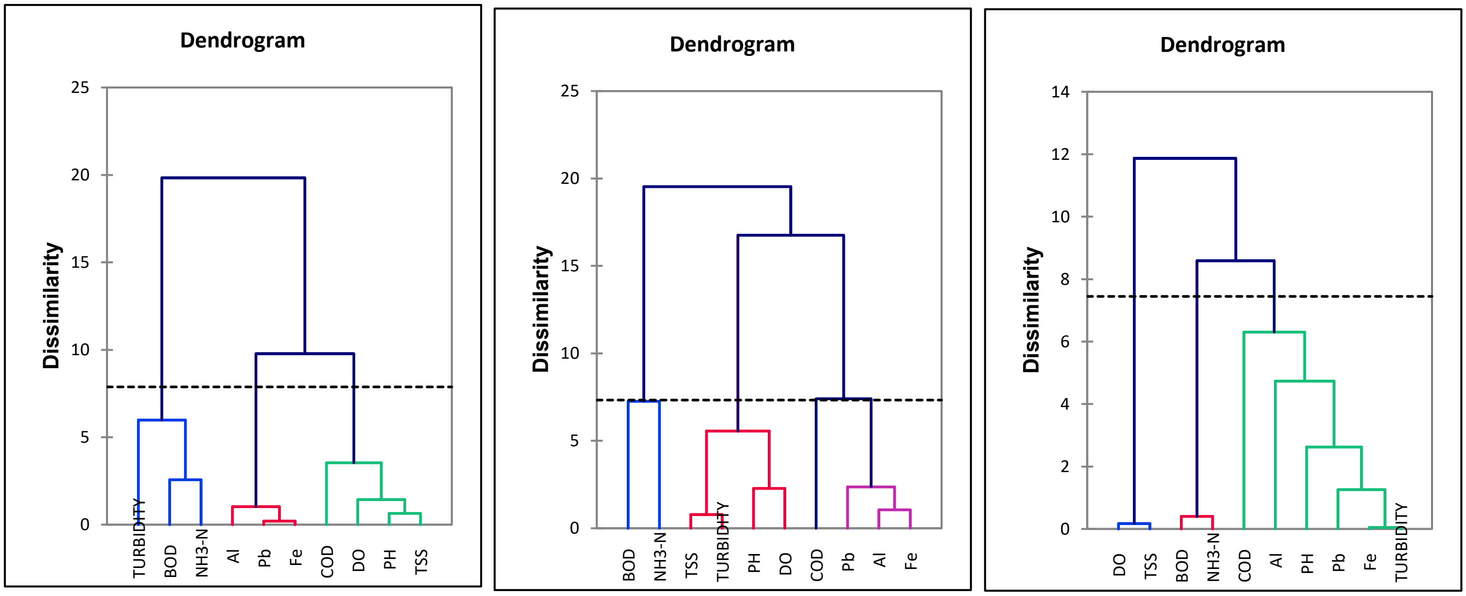

Figure 2. Dendrogram of AHC analysis of water quality parameters (ppm dry weight) in water samples of a) Sungai Kuantan, b) Sungai Riau, and c) Sungai Pinang

In Sungai Riau, the analysis also identified three major clusters. Cluster 1 contained BOD and NH3-N, suggesting a strong association between these organic pollution indicators. Cluster 2 was further divided into subclusters: Cluster 2.1, which included TSS and turbidity, and Cluster 2.2, which pH and DO. Meanwhile, COD, Pb, Al, and Fe were grouped in Cluster 3, highlighting their interrelation in influencing water quality characteristics.

Similarly, in Sungai Pinang, three primary clusters were observed. Cluster 1 was composed of DO and TSS, which are critical indicators of aquatic health. Cluster 3 was divided into two subclusters: Cluster 3.1, which grouped COD and Cluster 3.2, which contained Al, pH, Pb, Fe, and turbidity suggesting that these heavy metals share common sources or similar environmental behaviors and can contribute to Ph and turbidity of water. Overall, the cluster analysis effectively grouped water quality parameters and heavy metals, providing insights into pollution patterns and potential contamination sources. The formation of distinct clusters highlights the interdependencies among variables, which can be used for targeted water quality monitoring and management strategies. These patterns suggest that anthropogenic activities, particularly industrial discharges, mining, and manufacturing, may simultaneously introduce these metals into the aquatic environment. The clustering also aligns with previous studies, where metals with similar chemical behavior and mobility tend to group together [41, 42].

Comparisons with other studies further support the observed clustering trends. Pb and Zn have been reported in the same cluster in the Amaravathi River, likely due to irrigation practices and surface runoff [43]. Similarly, Mn, Cu, and Zn were clustered in the Subarnarekha River, where industrial effluents were identified as a key source [44]. In China, Zn and Pb were found together in the Yangping River, where contamination was linked to smelting activities near the river [34]. These findings suggest that variations in metal distribution can be attributed to specific sources of pollution and their geochemical behavior in river systems.

Conclusions

The findings had reported that water quality in Sungai Kuantan, Sungai Riau, and Sungai Pinang varied by river and season. Based on NWQS, temperature and turbidity were within safe limits (Class I), while DO and BOD were Class II. pH, COD, and TSS were Class III, and NH_3-N was Class IV. Water quality declined during the wet season compared to the dry season. This study also revealed that while seasonal variation had no significant difference on the water quality parameters measured, spatial differences between sampling stations were statistically significant. This indicates that local environmental and anthropogenic factors play a more influential role in shaping water quality in Sungai Kuantan than seasonal changes. Therefore, continuous spatial monitoring and targeted management strategies are essential, especially in areas affected by human activities. The Water Quality Index (WQI) classified Sungai Kuantan as Class II (WQI: 80.10–78.12), requiring conventional treatment, while Sungai Riau and Sungai Pinang fell under Class III (WQI: ~72–71), indicating slight pollution and the need for extensive treatment. Heavy metal analysis showed Fe was the most abundant in water sample of Sungai Kuantan (113.49 ppb) and Sungai Riau (275.74 ppb), while Al (25.81 ppb) was highest in Sungai Pinang during the wet season. However, all metals remained within NWQS (2021), WHO, and USEPA (2017) limits. The PCA biplot analysis showed that NH3-N, BOD, and turbidity strongly positively correlate with each other, while DO negatively correlates with BOD and NH3-N in all three rivers. pH, TSS, and COD exhibit positive correlations, whereas heavy metals like Pb, Fe, and Al are strongly correlated among themselves and moderately linked to COD. This study helps identify key water quality parameters influencing river pollution, allowing for targeted monitoring and management. While the findings provide valuable insights, we acknowledge the limitation in sampling design. Therefore, we recommend that future studies particularly those conducted in mining-impacted areas, adopt vertical profiling to better assess water column stratification and the vertical distribution of contaminants. By understanding the relationships between pollutants, authorities can implement more effective water treatment strategies, prioritize high-risk contaminants, and develop policies to mitigate pollution sources, ultimately improving river ecosystem health and water safety.

Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

Acknowledgment

The authors express their sincere gratitude to Universiti Sultan Zainal Abidin for providing the opportunity and support to conduct this research project.

References

[1] Ejigu, M. T. (2021). Overview of water quality modeling. *Cogent Engineering, 8*(1), 1891711. https://doi.org/10.1080/23311916.2021.1891711

[2] Coffey, R., Paul, M. J., Stamp, J., Hamilton, A., & Johnson, T. (2019). A review of water quality responses to air temperature and precipitation changes 2: Nutrients, algal blooms, sediment, pathogens. *JAWRA Journal of the American Water Resources Association, 55*(4), 844–868. https://doi.org/10.1111/1752-1688.12743

[3] Camara, M., Jamil, N. R., & Abdullah, A. F. B. (2019). Impact of land uses on water quality in Malaysia: A review. *Ecological Processes, 8*(1), 1–10. https://doi.org/10.1186/s13717-019-0188-5

[4] Chaudhary, M., & Walker, T. R. (2019). River Ganga pollution: Causes and failed management plans (correspondence on Dwivedi et al. 2018. Ganga water pollution: A potential health threat to inhabitants of Ganga basin. Environment International 117, 327–338). *Environment International, 126*, 202–206. https://doi.org/10.1016/j.envint.2019.02.039

[5] Fuschi, C., Pu, H., MacDonell, M., Picel, K., Negri, M., & Chen, J. (2022). Microplastics in the Great Lakes: Environmental, health, and socioeconomic implications and future directions. *ACS Sustainable Chemistry & Engineering, 10*(43), 14074–14091. https://doi.org/10.1021/acssuschemeng.2c03827

[6] Loi, J. X., Chua, A. S. M., Rabuni, M. F., Tan, C. K., Lai, S. H., Takemura, Y., & Syutsubo, K. (2022). Water quality assessment and pollution threat to safe water supply for three river basins in Malaysia. *Science of The Total Environment, 832*, 155067. https://doi.org/10.1016/j.scitotenv.2022.155067

[7] Amri, S. A. S., Bakar, A. A., & Baharuddin, Z. M. (2023). Restoring river ecological value at Sungai Pusu Gombak Selangor. *Design Ideals Journal, 5*(2). https://doi.org/10.37944/dij.v5i2.293

[8] Fatima, S. U., Khan, M. A., Siddiqui, F., Mahmood, N., Salman, N., Alamgir, A., & Shaukat, S. S. (2022). Geospatial assessment of water quality using principal components analysis (PCA) and water quality index (WQI) in Basho Valley, Gilgit Baltistan (Northern Areas of Pakistan). *Environmental Monitoring and Assessment, 194*(3), 151. https://doi.org/10.1007/s10661-022-09808-2

[9] Isiyaka, H. A., Mustapha, A., Juahir, H., & Phil-Eze, P. (2019). Water quality modelling using artificial neural network and multivariate statistical techniques. *Modeling Earth Systems and Environment, 5*, 583–593. https://doi.org/10.1007/s40808-018-0564-y

[10] Shafii, N. Z., Saudi, A. S. M., Pang, J. C., Abu, I. F., Sapawe, N., Kamarudin, M. K. A., & Saudi, H. F. M. (2019). Application of chemometrics techniques to solve environmental issues in Malaysia. *Heliyon, 5*(10), e02534. https://doi.org/10.1016/j.heliyon.2019.e02534

[11] Zakariah, M. N. A., Roslan, N., Sulaiman, N., Aznan, M. A., & Al Farishi, B. (2025). Hydro-geochemical assessment of groundwater quality of Muda River Basin, Kedah Malaysia. *Malaysian Journal of Fundamental and Applied Sciences, 21*(1), 1513–1528. https://doi.org/10.11113/mjfas.v21n1.3892

[12] APHA. (2017). *Standard methods for the examination of water and wastewater* (23rd ed., R. B. Baird, A. D. Eaton, & E. W. Rice, Eds.). American Public Health Association.

[13] Department of Environment. (2021). *National water quality standards for Malaysia – Annex*. http://www.wepa-db.net/policies/law/malaysia/eq_surface.htm

[14] Khalik, W. M. A. W. M., Abdullah, M. P., Farina, Y., Othman, M. R., Padli, N., & Amerudin, N. A. (2016). Water quality in selected tributaries of Kuantan River, Malaysia: An assessment after bauxite stockpile leaching incident.

[15] Razali, A., Ismail, S. N. S., Awang, S., Praveena, S. M., & Abidin, E. Z. (2018). Heavy metals contamination and potential health risk in highland river watershed (Malaysia). *Malaysian Journal of Medicine and Health Sciences*, *14*(Special Issue 1), 45–55.

[16] Chowdhury, M. S. U., Othman, F., Jaafar, W. Z. W., Mood, N. C., & Adham, M. I. (2018). Assessment of pollution and improvement measure of water quality parameters using scenarios modeling for Sungai Selangor Basin. *Sains Malaysiana, 47*(3), 457–469.

[17] Pak, H. Y., Chuah, C. J., Yong, E. L., & Snyder, S. A. (2021). Effects of land use configuration, seasonality and point source on water quality in a tropical watershed: A case study of the Johor River Basin. *Science of the Total Environment, 780*, 146661. https://doi.org/10.1016/j.scitotenv.2021.146661

[18] Abd Raoff, M. N. A., & Haris, M. N. (2018). Impact of hydrological study to water quality status in Sungai Kuantan, Pahang, Malaysia. *International Journal of Engineering & Technology, 7*(3.14), 35–43.

[19] Kozaki, D., Harun, N. I., Chong, C. H., Esraruddin, M. H., Yunus, N. A., Derahman, A. S., & Yusoff, M. (2019). Identification of polluted sites in four major rivers in Kuantan, Malaysia based on water chemistry estimates of aquatic microbial activity. *Sustainability, 11*(14), 3813. https://doi.org/10.3390/su11143813

[20] Omar, M. S., Hashim, M., Nayan, N., Zahid, M. S., Mahat, H., Saleh, Y., & See, K. L. (2022). Water quality of the Jerteh River Basin, Terengganu, Malaysia during the Northeast Monsoon. In *IOP Conference Series: Earth and Environmental Science, 975*(1), 012002. https://doi.org/10.1088/1755-1315/975/1/012002

[21] Hashem, A. O. A., Ahmad, W. A. A. W., & Yusuf, S. Y. (2021). Water quality status of Sungai Petani River, Kedah, Malaysia. In *IOP Conference Series: Earth and Environmental Science, 646*(1), 012028. https://doi.org/10.1088/1755-1315/646/1/012028

[22] Ab Wahab, S. U. K., Hairuddin, H. F., Aris, M. S. M., & Khan, A. J. (2021). Analysis of water quality parameters using environmetric technique for health risk assessment of rivers pollution sources pre-COVID-19 pandemic in Gebeng Industrial Area, Pahang, Malaysia. *Malaysian Journal of Medicine and Health Sciences*, 17(Suppl 1), 19–27.

[23] Alam, M. Z., Kabbashi, N. A., Sukri, N. A. N. M., & Abdullah, N. (2023). A case study on assessment and rehabilitation of IIUM Pusu River for water quality improvement.

[24] Kamarudin, M. K. A., Abd Wahab, N., Bati, S. N. A. M., Toriman, M. E., Saudi, A. S. M., & Umar, R. (2020). Seasonal variation on dissolved oxygen, biochemical oxygen demand and chemical oxygen demand in Terengganu River Basin, Malaysia. *Journal of Environmental Science and Management, 23*(2), 40–50.

[25] Masthurah, A., Juahir, H., & NB, M. Z. (2023). Case study Malaysia: Spatial water quality assessment of Juru, Kuantan and Johor River Basins using environmetric techniques. *Journal of Survey in Fisheries Sciences*, *10*(4S), 19–40.

[26] Hanafiah, M. M., Yussof, M. K. M., Hasan, M., AbdulHasan, M. J., & Toriman, M. E. (2018). Water quality assessment of Tekala River, Selangor, Malaysia. *Applied Ecology and Environmental Research, 16*(4), 5157–5174. https://doi.org/10.15666/aeer/1604_51575174

[27] United States Environmental Protection Agency (USEPA). (2012). *EPA Region III Risk-Based Concentration (RBC) Table 2008*. U.S. Environmental Protection Agency, Region III, 1650 Arch Street, Philadelphia, PA.

[28] Abdullah, N. H., Mohamed, N., Sulaiman, L. H., Zakaria, T. A., & Rahim, D. A. (2016). Potential health impacts of bauxite mining in Kuantan. *The Malaysian Journal of Medical Sciences: MJMS, 23*(3), 1–12.

[29] ATDSR (2008). Toxological Profil for Aluminium, U.S. Department of Health and Human Services, September 2008.

[30] Inan-Eroglu, E., & Ayaz, A. (2018). Is aluminum exposure a risk factor for neurological disorders? *Journal of Research in Medical Sciences: The Official Journal of Isfahan University of Medical Sciences, 23*, 51. https://doi.org/10.4103/jrms.JRMS_949_17

[31] Agency for Toxic Substances and Disease Registry (ATSDR). (2008). *Toxicological profile for aluminium*. U.S. Department of Health and Human Services. https://www.atsdr.cdc.gov/toxprofiles/tp22.pdf

[32] United States Environmental Protection Agency (EPA). (2000). *Guidance for data quality assessment: Practical methods for data analysis (EPA QA/G-9)*. https://www.epa.gov/sites/default/files/2015-06/documents/g9-final.pdf

[33] Khound, N. J., & Bhattacharyya, K. G. (2017). Multivariate statistical evaluation of heavy metals in the surface water sources of Jia Bharali River Basin, North Brahmaputra Plain, India. *Applied Water Science, 7*, 2577–2586. https://doi.org/10.1007/s13201-016-0449-1

[34] Lee, J. W., Choi, H., Hwang, U. K., Kang, J. C., Kang, Y. J., Kim, K. I., & Kim, J. H. (2019). Toxic effects of lead exposure on bioaccumulation, oxidative stress, neurotoxicity, and immune responses in fish: A review. *Environmental Toxicology and Pharmacology, 68*, 101–108. https://doi.org/10.1016/j.etap.2019.03.009

[35] Kamarudin, M. K. A., Abd Wahab, N., Bati, S. N. A. M., Toriman, M. E., Saudi, A. S. M., & Umar, R. (2020). Seasonal variation on dissolved oxygen, biochemical oxygen demand and chemical oxygen demand in Terengganu River Basin, Malaysia. *Journal of Environmental Science and Management, 23*(2), 40–50.

[36] Asim, M., & Nageswara Rao, K. (2021). Assessment of heavy metal pollution in Yamuna River, Delhi-NCR, using heavy metal pollution index and GIS. *Environmental Monitoring and Assessment, 193*(2), 103. https://doi.org/10.1007/s10661-020-08843-9

[37] Kusin, F. M., Rahman, M. S. A., Madzin, Z., Jusop, S., Mohamat-Yusuff, F., & Ariffin, M. (2016). The

occurrence and potential ecological risk assessment of bauxite mine-impacted water and sediments in Kuantan, Pahang, Malaysia. *Environmental Science and Pollution Research, 24*(2), 1306–1321. https://doi.org/10.1007/s11356-016-7907-z

[38] Othman, F., Chowdhury, M. U., Wan Jaafar, W. Z., Faresh, E. M., & Shirazi, S. M. (2018). Assessing risk and sources of heavy metals in a tropical river basin: A case study of the Selangor River, Malaysia. *Polish Journal of Environmental Studies, 27*(4), 1605–1614. https://doi.org/10.15244/pjoes/76804

[39] Pratama, M. A., Immanuel, Y. D., & Marthanty, D. R. (2020). A multivariate and spatiotemporal analysis of water quality in Code River, Indonesia. *The Scientific World Journal, 2020*(1), 8897029. https://doi.org/10.1155/2020/8897029

[40] Agrawal, S., Sharma, A., & Shivhare, S. (2025). Comprehensive assessment of Narmada River water quality using correlation matrices and water quality indices: A case study. In *Blue sky, blue water: Strategies for protecting air and water quality in the 21st century* (pp. 55–69). Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-29494-5_5

[41] Wei, H., Yu, H., Zhang, G., Pan, H., Lv, C., & Meng, F. (2018). Revealing the correlations between heavy metals and water quality, with insight into the potential factors and variations through canonical correlation analysis in an upstream tributary. *Ecological Indicators, 90*, 485–493. https://doi.org/10.1016/j.ecolind.2018.03.051

[42] Ahamed, A. J., & Loganathan, K. (2017). Water quality concern in the Amaravathi River Basin of Karur district: A view at heavy metal concentration and their interrelationships using geostatistical and multivariate analysis. *Geology, Ecology, and Landscapes, 1*(1), 19–36. https://doi.org/10.1080/24749508.2017.1310031

[43] Manoj, K., Kumar, B., & Padhy, P. K. (2012). Characterisation of metals in water and sediments of Subarnarekha River along the projects' sites in lower basin, India. *Universal Journal of Environmental Research & Technology, 2*(5), 402–410

[44] Liu, Y., Yu, H., Sun, Y., & Chen, J. (2017). Novel assessment method of heavy metal pollution in surface water: A case study of Yangping River in Lingbao City, China. *Environmental Engineering Research, 22*(1), 31–39. https://doi.org/10.4491/eer.2016.079

[45] Yazdanabdad, T. E., Forghaniha, A., Emtyazjoo, M., & Ramezani, M. (2022). *Toxicity effects of engineered iron nanoparticles (Fe_3O_4) on the growth, cell density, and pigment content of Chlorella vulgaris.* Archives of Environmental Contamination and Toxicology, 83(2), 155–167. https://doi.org/10.1007/s00244-022-00949-0