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Research article

# Seasonal assessment of surface water and sediments pollution in Rachiine River, Northern Lebanon, using multivariate statistical analysis

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ABSTRACT

Urbanization has caused severe negative impacts on intra-urban river water worldwide. In this study, the WHO drinking water standards (2024) were used as reference to assess the physicochemical properties, heavy metals (HMs) content and microbial load in water and sediment samples collected from 25 locations along Rachiine River, located in Northern Lebanon, during wet and dry periods. Multivariate statistical analysis was applied to evaluate the seasonal variations in water and sediment quality, and determine the pollution sources. The microbial load assessment indicated high pollution levels by *Escherichia coli*, fecal enterococci, total coliform and fecal coliform, which generally increased as the river progressed downstream. Cluster analysis (CA) provided three major clusters in the study region, representing the northern, central, and southern sectors of the river. Principal components analysis (PCA) of water samples generated four principal components (PCs) accounting for 64.3, 11.4, 7.6 and 4.1 % of the total variance, whereas PCA of sediment samples explained 59.1, 16.9 and 11.1 % of the data set variance. These PCs revealed that the quality of water and sediments is significantly impacted by point and diffuse sources, including geological and anthropogenic factors. These findings call for urgent management strategies to limit future deterioration of the aquatic bodies.

## 1. Introduction

Water is considered as one of Earth's vital resources, and monitoring its quality is crucial for the well-being of all living organisms [1,2]. Nevertheless, water bodies can vary in quality and availability depending on their degree of exposure to anthropogenic as well as natural activities [3,4]. Based on studies issued by the World Health Organization, over half of the world population would be exposed to severe water scarcity by 2025 [5]. Industrialization and urbanization impacted water quality negatively, especially through agricultural and industrial outpour containing harsh chemicals and microorganisms [6]. In addition, water quality has decreased immensely mainly due to the extensive and uncontrolled use of pesticides and fertilizers [7]. On the other hand, developing countries

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did not put in place the needed infrastructure for wastewater collection and treatment which led to contamination of surface water [8]. In developing countries, fecal contamination was the main source of poor water quality [9]. Thus, surface water should be continuously tested for its biological and physicochemical parameters [10]. The WHO drinking water standards, updated in 2024, provide comprehensive guidelines designed to evaluate water quality globally. These guidelines specify maximum permissible concentrations for various contaminants, including heavy metals, pathogens, and chemical pollutants, to ensure water safety for human consumption [11]. Many indicators can assist in the assessment of microbiological contamination of water. These include fecal indicator bacteria that are members of the normal flora of the gastrointestinal tracts of humans and other warm-blooded animals [12]. Fecal indicators include total coliforms (TC), fecal coliforms (FC) (a group of bacteria within the TC), and *Escherichia coli* (*E. coli*) (a specific species of FC) that can spread through the fecal material and wastewater in different environments, including soil and vegetables [13].

Over the last decades, heavy metals contamination has alarmed the public and scientists due to their chronic toxicity, ability to infiltrate the food chain, tendency to bioaccumulate in the environment, and chemical stability against biodegradation [14–17]. Due to their low solubility in water, most HMs accumulate in the bottom sediments and minor fraction remain suspended in the water column [18]. River sediments play a pivotal role in the adsorption and transportation of HMs within aquatic ecosystems [19,20]. Therefore, sediment quality serves as a valuable parameter for assessing the impact of anthropogenic activities on natural resources and guides policy and management decisions in surrounding areas [20–22].

Lebanon, a small country in the Middle East, is well-endowed with water resources that are essential for agricultural (60 %), municipal (29 %), and industrial (11 %) practices [23,24]. The country is characterized by a Mediterranean climate with a dry summer, moderately warm autumn, and windy and wet winter, with nearly 80–90 % of the total rainfall occurring between November

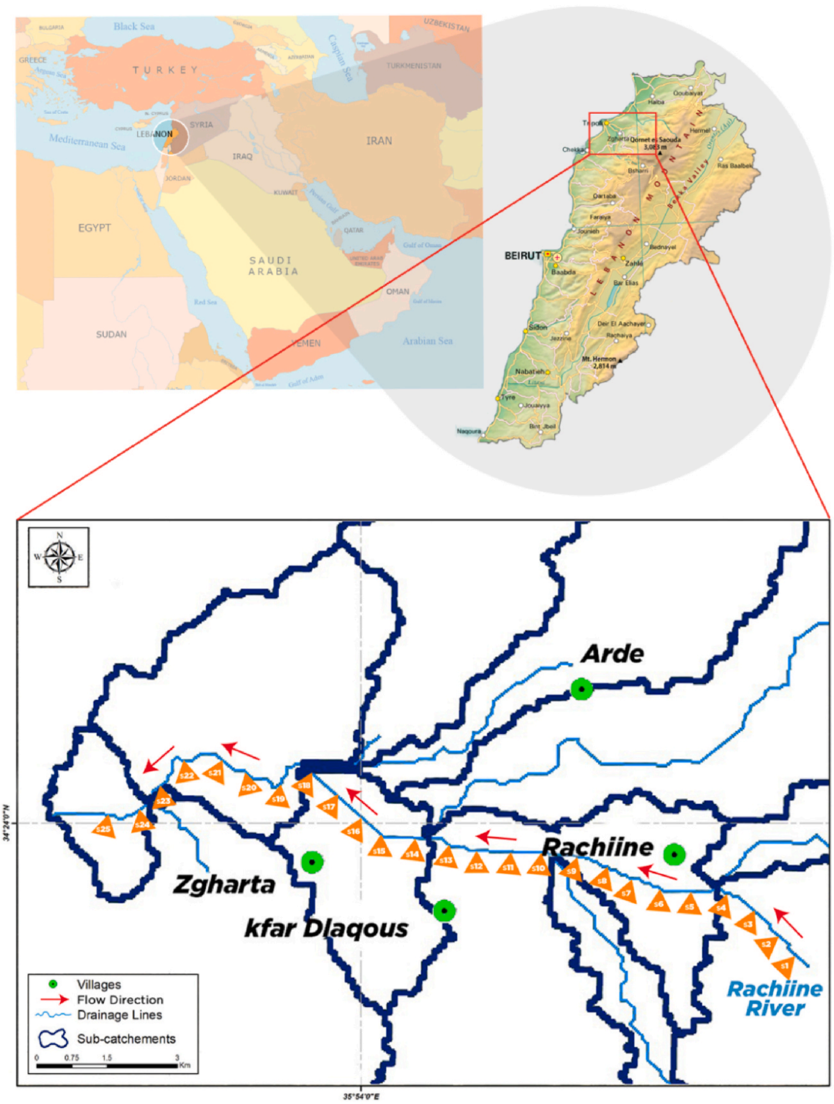


**Fig. 1.** Location map for the study area. Sampling sites are indicated by orange triangles.

and March [25]. Lebanon is facing problems of inadequate infrastructure and ineffective wastewater management [26,27]. Moreover, 63 % of the buildings directly discharge wastewater in septic tanks or river courses that can be used for direct consumption without any treatment [28]. These environmental issues alongside various agricultural and industrial waste products, significantly harm the aquatic ecosystems [29,30].

The main Northern Lebanese rivers (i.e. Kadicha, El Kebir, and El Bared) are subject to urban and agricultural pressures [31]. Rachiine River, a stream of Kadisha River, extends for 44.5 Kilometers, flowing through 95 cities and villages, with an annual average discharge rate of 262 million $m^3$ [28,32]. The river catchment encompasses an area of approximately 491 $Km^2$. The study area features a typical Mediterranean climate, characterized by mild winters and moderately hot summers along the coast. However, as elevation increases, winter becomes colder, and precipitation becomes more frequent, often falling as snow on the highest peaks. Consequently, snowmelt serves as an important water source in the river watershed, in addition to rainfall [31]. The average annual precipitation is approximately 1600 mm at the river's sources, decreasing to around 700 mm at the coastal area. The average river flows for the dry season and wet season are about 0.8 $m^3/s$ and 17.2 $m^3/s$, respectively [25]. The river flow is monitored by the Litani River Authority (LRA) via a fixed station at the river (Latitude: 34:24:14, Longitude: 35:53:15) [28]. According to the land cover and use map of the river watershed [33], urban areas constitute 6.8 % while agricultural land accounts for 27.2 % of the total watershed area, highlighting agriculture as a primary economic activity in the region and a significant contributor to water pollution. Natural areas cover about 65.9 % of the basin, including grasslands (27.9 %), forests (17.8 %), shrubs (11.6 %), and bare lands (8.6 %).

Rachiine River is highly influenced by rapid urbanization and demographic expansion in addition to the industrial activities of Zgharta city [34] with an average waste discharge rate estimated at 350–400 tonnes per day [28]. With the absence of a wastewater treatment plan, such activities further deteriorate the water quality of the river and render it unsuitable for domestic and agricultural uses. Zgharta has undergone considerable urbanization over the past four decades with an estimated population of 100,000. This population increased after the Syrian crisis with an influx of 12,311 refugees (around 2884 families) who are living in informal settlements and areas lacking public sanitation, potentially leading to increased anthropogenic pressure on nearby aquatic bodies [35,36]. Rachiine spring water is widely distributed over 36 towns in North Lebanon which can be a major contributor of domestic sewage into the aquatic ecosystems. However, no comprehensive research was reported on the Rachiine River in North Lebanon, which is highly influenced by multiple anthropogenic activities (dairy industries, olive presses, agricultural activities, and urbanization) that can lead to the introduction of different forms of pollutants into the water. Thus, we conducted this study to assess the physicochemical, heavy metal, and microbiological contamination of the water and sediment samples collected from Rachiine River.

## 2. Methods

### 2.1. Sampling procedure

Twenty-five different sampling sites (S1 to S25) were selected (Fig. 1 and Table S1) along Rachiine River. The sampling sites were located 200–250 m apart to ensure comprehensive coverage of the entire river. Sediment and water samples were collected over two sampling periods: i) the dry period including July 2020 and April 2021, and ii) the wet period including October 2020 and January 2021 according to the AQUAREF methods [37].Water samples were collected in duplicate at each site. Superficial sediments were obtained using a manual hand auger, from approximately 4 cm depth, and stored in high-grade polyethylene bags. All collected samples were transported immediately after collection in a cooler with ice packs to the laboratory at Beirut Arab University where they were filtered using a 0.45-μm Whatman filter and then stored for further analysis. For bacteriological assessment, a 50 mL sample was processed within 6 h of sampling. The 2024 WHO drinking water standards were used as a reference to evaluate the physicochemical properties, HMs concentrations, and microbial contamination in both water and sediment samples [11].

### 2.2. Physicochemical parameters

Physicochemical parameters were investigated in water and sediment samples in accordance with standard methods [38–40]. The pH, electrical conductivity (EC), temperature (TEM), salinity (SAL), total dissolved solids (TDS) (mg/L), and dissolved oxygen (DO) (mg/L) were determined in situ using Thermo Orion (Thermo Fisher Scientific, USA). Turbidity was measured with Lovibond Water Testing Turbidimeter (Tintometer Group, UK). Nutrient species, namely nitrate ($NO_3^-$), phosphate ($PO_4^{3-}$), and sulfate ($SO_4^{2-}$), were determined photometrically using a photometric analyzer (Thermo Spectronic, US). Chemical oxygen demand (COD) was determined following standard protocols for reflux digestion and titration [38]. All metal analysis in water samples (mg/L) and sediments (μg/mg) were performed using an atomic absorption spectrophotometer (Thermo Scientific, Graphite flame ICE 3500).

The measurement errors of the instruments used for assessing the physicochemical parameters varied according to the specific device and parameter. The Thermo Orion pH meter had an accuracy of ±0.002 pH units, the conductivity meter ±0.5 % of the reading, and the dissolved oxygen meter ±0.1 mg/L. The Lovibond turbidimeter exhibited a measurement error of ±0.01 NTU, with a range from 0 to 1100 NTU. The photometric analyzer had an absorbance accuracy of ±0.005 Abs, with a range from 0 to 3 Abs. Chemical Oxygen Demand (COD) analysis using reflux digestion and titration had a measurement error between ±2–5%. The atomic absorption spectrophotometer showed measurement errors ranging from ±0.5 % to ±2 %, depending on the element and concentration range.

### 2.3. Microbiological analysis

Water samples were processed for microbiological analysis of fecal contamination (TC, FC, *E. coli* and enterococci (ENT)) using membrane filtration method for testing TC (protocol 9222B), FC (protocol 9222D17), and ENT (USEPA Method 1600) [41]. Fifty milliliters of water were vacuum-filtered (pore size 0.22 μm, diameter 47 mm; Millipore) in triplicate, and the filters were transferred to m-Endo, m-FC, and Enterococcus Selective Agar plates (Sigma-Aldrich, USA) for TC, FC, and ENT bacteria, respectively. The plates were incubated at 37 °C for 24 h for TC and 48 h for ENT. FC plates were incubated at 44.5 °C for 24 h. Isolated colonies were examined for their morphological characteristics, and their abundance was reported as colony-forming units (CFU) per 100 mL of water.

### 2.4. Data analysis

For the physicochemical parameters, the results were expressed as the mean ± standard deviation (SD). One-way ANOVA was applied to determine statistically significant spatial and seasonal variation (p-value<0.05). PCA was used to reduce the dimensionality

**Table 1**
Statistical summary of physical and chemical parameters of the river water over the sampling periods.

| Parameters | | Season | | | | International standards |
|---|---|---|---|---|---|---|
| | | July | October | January | April | (WHO, 2022) |
| **Physicochemical parameters** | | | | | | |
| pH | Mean ± SD | 7.8 ± 0.2 | 8 ± 0.4 | 8 ± 0.2 | 8 ± 0. | 6.5–85 |
| | [Min. – Max.] | [7.5–8.3] | [7.3–8.9] | [7.6–8.6] | [7.8–8.4] | |
| BOD | Mean ± SD | 2.4 ± 1.6 | 3.8 ± 2.3 | 2.5 ± 1.7 | 3.2 ± 2.2 | <5 mg/L |
| | [Min. – Max.] | [0.5–4.9] | [1.4–8.3] | [0.4–5.9] | [0.3–6.8] | |
| EC | Mean ± SD | 0.4 ± 0.08 | 0.57 ± 0.14 | 0.39 ± 0.07 | 0.35 ± 0.08 | 0.20–1.5 mS/cm |
| | [Min. – Max.] | [0.24–0.5] | [0.24–0.66] | [0.24–0.47] | [0.11–0.47] | |
| TDS | Mean ± SD | 259 ± 49 | 350 ± 85 | 251 ± 42 | 222 ± 51 | 500 mg/L |
| | [Min. – Max.] | [155−321] | [154−424] | [154−299] | [70−302] | |
| COD | Mean ± SD | 5.1 ± 3.4 | 8.2 ± 5 | 5.3 ± 3.7 | 6.9 ± 4.7 | 250 mg/L |
| | [Min. – Max.] | [1–10.3] | [2.9–17.7] | [0.9–12.5] | [0.7–14.5] | |
| TEM | Mean ± SD | 22 ± 1.2 | 18.8 ± 1.4 | 12.9 ± 2.2 | 16.6 ± 1.1 | 25–30 °C |
| | [Min. – Max.] | [20–24] | [16–21] | [6–16] | [14–18.5] | |
| Turbidity | Mean ± SD | 2.7 ± 2.4 | 4.3 ± 4. | 5.5 ± 7.2 | 4.3 ± 5.1 | <5 NTU |
| | [Min. – Max.] | [0.05–9.6] | [0.1–12.9] | [0.1–34.9] | [0.1–19.7] | |
| **Nutrient Concentrations** | | | | | | International standards (WHO, 2022) |
| $NO_3^-$ | Mean ± SD | 9.5 ± 2.8 | 13.3 ± 6.4 | 8.6 ± 2.1 | 7.8 ± 2.5 | 45 mg/L |
| | [Min. – Max.] | [3.8–13.7] | [3.2–25.7] | [3.7–11.8] | [3–10.4] | |
| $SO_4^{2-}$ | Mean ± SD | 11.22 ± 3.51 | 14.49 ± 4.73 | 11.2 ± 4.41 | 9.79 ± 3.96 | 250 mg/L |
| | [Min. – Max.] | [4.4–18.8] | [4.4–22.2] | [4.4–19.2] | [3.4–17.4] | |
| $PO_4^{3-}$ | Mean ± SD | 0.07 ± 0.07 | 0.22 ± 0.21 | 0.05 ± 0.055 | 0.05 ± 0.05 | 0.35–0.5 mg/L |
| | [Min. – Max.] | [0–0.21] | [0–0.65] | [0–0.25] | [0–0.12] | |
| **Heavy Metal concentrations** | | | | | | Water permissible limits (WHO, 2022) |
| Arsenic | Mean ± SD | 0.02 ± 0.00 | 0.01 ± 0.00 | 0.14 ± 0.06 | 0.01 ± 0.00 | 0.01 mg/L |
| | [Min. – Max.] | [0.01–0.02] | [0.01–0.02] | [0.01–0.26] | [0.01–0.01] | |
| Cadmium | Mean ± SD | 0.28 ± 0.26 | 0.43 ± 0.42 | 0.62 ± 0.63 | 0.35 ± 0.31 | 0.003 mg/L |
| | [Min. – Max.] | [0.11–1.39] | [0.18–2.38] | [0.24–3.43] | [0.14–1.74] | |
| Chromium | Mean ± SD | 0.73 ± 0.25 | 0.82 ± 0.29 | 0.96 ± 0.46 | 0.95 ± 0.26 | 0.05 mg/L |
| | [Min. – Max.] | [0.14–1.17] | [0.16–1.35] | [0.14–3.88] | [0.3–1.5] | |
| Copper | Mean ± SD | 0.002 ± 0.001 | 0.002 ± 0.001 | 0.003 ± 0.001 | 0.002 ± 0.001 | 1 mg/L |
| | [Min. – Max.] | [0.001–0.004] | [0.001–0.003] | [0.001–0.06] | [0.001–0.004] | |
| Lead | Mean ± SD | 0.003 ± 0.002 | 0.005 ± 0.003 | 0.002 ± 0.0015 | 0.002 ± 0.0017 | 0.015 mg/L |
| | [Min. – Max.] | [0.001–0.01] | [0.001–0.01] | [0.001–0.01] | [0.001–0.01] | |
| Zinc | Mean ± SD | 1.37 ± 0.03 | 1.40 ± 0.03 | 1.40 ± 0.03 | 1.39 ± 0.03 | 4 mg/L |
| | [Min. – Max.] | [1.25–1.41] | [1.28–1.44] | [1.28–1.44] | [1.28–1.44] | |

of the dataset and reveal new factors, while CA was applied to investigate similarities and differences. Cluster analysis was performed using the average linkage method to identify patterns and groupings among the measured parameters. In this method, the distance between clusters is defined as the average distance between all pairs of objects, one from each cluster. This approach ensures that the clustering process considers the overall similarity between groups rather than the closest or furthest points [42]. PCA was performed to identify the primary sources of pollution in the river. PCA is a powerful technique for dimensionality reduction, allowing a smaller number of variables to effectively represent the original dataset [43]. The suitability of the data for factor analysis was assessed using the Kaiser-Meyer-Olkin (KMO) measure and Bartlett's test of sphericity. A KMO value greater than 0.5 and a Bartlett's test result with $p < 0.05$ indicated that the data were appropriate for conducting PCA [44]. This method enables the conversion of the original raw variables into integrated variables called principal components (PCs). PCs with eigenvalues greater than one were then identified [45]. The normality of the water and sediment data was primary assessed by IBM SPSS (Statistical Package for the Social Sciences) Ver. 29, using the One-Sample Kolmogorov-Smirnov test ($p > 0.05$).

## 3. Results and discussion

Only very few studies have investigated water chemical pollution in Northern Lebanon in the past two decades. Some studies were limited to the organic sediment pollution in Tripoli harbor [46], while others identified the concentrations of polyaromatic hydrocarbons (PAHs) in the sediments of coastal zones [47]. Moreover, Merhabi and coworkers [48] have conducted an ecological risk assessment of pharmaceutical products in the Kadicha River in Lebanon. Another study has evaluated the levels of HMs, total petroleum hydrocarbons, and microbial contaminations in fish from the marine area of Tripoli [49]. However, to date, no studies have been conducted to investigate the levels of health-threatening microbial contamination and chemical toxicity in water sources and sediments of North Lebanon. Thus, this study aimed to provide a thorough evaluation of the physicochemical properties and microbial contamination of Rachiine River.

### 3.1. Physicochemical properties of water samples

Lebanon is in a relatively fortunate hydrological position as compared to its neighboring Middle Eastern countries, with annual precipitation totals estimated to be 1222 mm in North-Lebanon [28,50]. In this study, the monthly averages of precipitation varied between 0 (during the months of June, July, August, September, and October) and 298.8 mm (during the month of January 2021) (Table S2). An important parameter that influences the quality of aquatic ecosystems such as the reproduction and metabolism of many aquatic species is water temperature [51]. In the current study, water temperature levels displayed significant variations across the different sampling periods, aligning with seasonal fluctuations ($p < 0.01$), with the lowest temperature recorded at 7 °C (January) and the highest recorded at 24 °C (July) (Table S2). These values were within the limits set by WHO for aquatic life and household activities, including drinking purposes. According to Table 1, pH levels in all sampling sites fell within the safe range (between 6 and 9) and the recorded values were leaning more toward an alkaline pH. This could be linked to increased microbial activities and decreased plant photosynthesis, surface runoff, and effluent percolation [52].

Turbidity levels were relatively higher during the wet season, but within the WHO recommended limits of 5 NTU [11]. This can be attributed to runoff of organic and inorganic matter (especially soil particles) [53], or high levels of pathogenic microorganisms such as bacteria and parasites [54]. The lowest turbidity was recorded in the upstream course and increased downstream of the river (Table S3). Such observation may be attributed to lower levels of soil erosion and water runoff upstream at the river's source compared to other sites where human activities have likely increased runoff and soil erosion. Furthermore, EC values fall within the permissible limits for drinking (0.7 mS/cm) and irrigation (1 mS/cm) water set by WHO [5]. EC and TDS levels displayed an upward trend downstream of the river from S1 to S25 (Table S3), and the highest value was recorded in the October sampling period (Table 1). In addition, statistical analysis showed a significant difference among the seasonal EC values (p-value$< 0.01$) (Table 4). These findings may be attributed to elevated chloride ion concentrations originating from domestic sewage and agricultural activities, which enhance water EC and nutrient enrichment.

An increasing trend in BOD was observed as the river progressed downstream (Table S3). This may be due to the untreated/partially treated effluents that are discharged directly into the river from various neighboring villages [53]. The BOD content is higher

**Table 2**
Statistical summary of microbial indicator counts from the sampling sites on the river.

| Parameters | | Season | | | | International standards |
|---|---|---|---|---|---|---|
| | | July | October | January | April | (WHO, 2022) |
| Total coliform | Mean ± SD<br>[Min. – Max.] | $5.7 \times 10^5 \pm 1.1 \times 10^6$<br>[36–4.1 x $10^6$] | $2.0 \times 10^6 \pm 4.2 \times 10^6$<br>[31–1.7 x $10^7$] | $7.5 \times 10^5 \pm 9.5 \times 10^5$<br>[0–3.3 x $10^6$] | $2.6 \times 10^5$ $5.9 \times 10^4$<br>[8–1.1 x $10^6$] | <1 CFU/100 mL |
| Fecal coliform | Mean ± SD<br>[Min. – Max.] | $4.1 \times 10^5 \pm 7.1 \times 10^5$<br>[4–2.4 x $10^6$] | $1.5 \times 10^6 \pm 3 \times 10^6$<br>[6 - 1 x $10^7$] | $3 \times 10^5 \pm 3.7 \times 10^5$<br>[0–1.5 x $10^6$] | $3.1 \times 10^5 \pm 8.5 \times 10^5$<br>[2–4.3 x $10^6$] | <1 CFU/100 mL |
| *E. coli* | Mean ± SD<br>[Min. – Max.] | $2 \times 10^5 \pm 4.1 \times 10^5$<br>[1–1.5 x $10^6$] | $4.6 \times 10^5 \pm 1.1 \times 10^6$<br>[1–4.7 x $10^6$] | $6.9 \times 10^4 \pm 7.4 \times 10^4$<br>[0–2.6 x $10^5$] | $5.9 \times 10^4 \pm 7 \times 10^4$<br>[0–2.1 x $10^5$] | <1 CFU/100 mL |
| Fecal Enterococci | Mean ± SD<br>[Min. – Max.] | $1.5 \times 10^4 \pm 2 \times 10^4$<br>[0–6.5 x $10^4$] | $5.2 \times 10^4 \pm 7.2 \times 10^4$<br>[0–2.4 x $10^5$] | $1.2 \times 10^4 \pm 1.9 \times 10^4$<br>[0–8.2 x $10^4$] | $2.2 \times 10^4 \pm 4.5 \times 10^4$<br>[0–2.2 x $10^5$] | <1 CFU/100 mL |

**Table 3**
Statistical summary of physical and chemical parameters of the river sediment over the sampling periods.

| Parameters | | Season | | | | Unit |
|---|---|---|---|---|---|---|
| | | July | October | January | April | |
| **Physicochemical parameters** | | | | | | |
| pH | Mean ± SD | 6.8 ± 0.3 | 6.9 ± 0.2 | 7.3 ± 0.1 | 6.9 ± 0.1 | – |
| | [Min. – Max.] | [6.2–7.4] | [6.6–7.2] | [7.2–7.5] | [6.7–7.2] | |
| EC | Mean ± SD | 0.4 ± 0.5 | 0.6 ± 0.6 | 0.2 ± 0.1 | 0.2 ± 0.1 | mS/cm |
| | [Min. – Max.] | [0.1–1.7] | [0.12–1.9] | [0.07–0.54] | [0.08–0.64] | |
| TP | Mean ± SD | 85 ± 64 | 120 ± 108 | 60 ± 33 | 121 ± 109 | mg/L |
| | [Min. – Max.] | [23−268] | [22−459] | [14_130] | [22−459] | |
| TN | Mean ± SD | 0.24 ± 0.24 | 0.34 ± 0.28 | 0.19 ± 0.13 | 0.29 ± 0.17 | % |
| | [Min. – Max.] | [0.06–1.04] | [0.08–1.21] | [0.02–0.54] | [0.03–0.65] | |
| OM | Mean ± SD | 4.0 ± 3.9 | 5.7 ± 4.6 | 3.2 ± 2.2 | 4.8 ± 2.9 | 2–7 % |
| | [Min. – Max.] | [1–17.3] | [1.4–20.2] | [0.3–9.1] | [0.6–10.9] | |
| **Heavy Metal concentrations** | | | | | | Target value of soil (mg/kg)[a] |
| Arsenic | Mean ± SD | 0.02 ± 0.04 | 0.03 ± 0.09 | 0.027 ± 0.07 | 0.09 ± 0.21 | 6 |
| | [Min. – Max.] | [0.01–0.2] | [0.01–0.41] | [0.01–0.31] | [0.01–0.88] | |
| Cadmium | Mean ± SD | 0.08 ± 0.07 | 0.08 ± 0.03 | 0.11 ± 0.05 | 0.12 ± 0.11 | 0.8 |
| | [Min. – Max.] | [0.01–0.29] | [0.01–0.14] | [0.03–0.19] | [0.01–0.53] | |
| Chromium | Mean ± SD | 1.50 ± 1.65 | 1.29 ± 1.15 | 1.15 ± 0.47 | 1.07 ± 1.14 | 13 |
| | [Min. – Max.] | [0.16–6.35] | [0.23–5.7] | [0.42–1.9] | [0.14–5.62] | |
| Copper | Mean ± SD | 0.05 ± 0.03 | 0.04 ± 0.04 | 0.34 ± 0.58 | 0.12 ± 0.24 | 36 |
| | [Min. – Max.] | [0–0.1] | [0–0.17] | [0.01–2.55] | [0–1.09] | |
| Lead | Mean ± SD | 1.52 ± 1.24 | 1.10 ± 0.79 | 1.62 ± 1.04 | 1.36 ± 1.11 | 85 |
| | [Min. – Max.] | [0.23–4.4] | [0.28–3.33] | [0.32–3.94] | [0.26–3.92] | |
| Zinc | Mean ± SD | 2.86 ± 2.01 | 2.87 ± 1.80 | 4.48 ± 0.87 | 2.12 ± 1.54 | 50 |
| | [Min. – Max.] | [0.8–6.21] | [0.93–6.75] | [3.2–6.96] | [0.89–6.55] | |

[a] Target values are specified to indicate desirable maximum levels of elements in unpolluted soils (WHO 1996).

in the wet season than in the dry season due to increased surface runoff and rainfall discharged into river water. The presence of excessive bacteria/microorganisms originating from industrial and domestic wastewater results in high BOD levels due to the consumption of dissolved oxygen in the river water. Moreover, high COD values are potentially linked to the growth of microorganisms which increases significantly when water flow declines in the dry season [55]. High COD levels can result in reduced dissolved oxygen in water environments, thus causing significant stress to aquatic life [56]. During all sampling periods, measurable COD was recorded. Higher COD values imply greater degrees of pollution of the river system with oxidizable organic matter (biodegradable and non-biodegradable), which can originate from animal farms, domestic, and industrial discharges.

Moreover, the levels of nutrients ($NO_3^-$, $PO_4^{3-}$, and $SO_4^{2-}$) were analyzed (Table 1). Higher averages of nitrate concentrations were recorded during the rainy season. This can be attributed to the discharge of anthropogenic wastewater into the river. In addition, it can be sourced from the remineralization of bottom sediments, which are suspended after dredging and sourced from mudflats [57]. Generally, when nutrients come from upstream, they are mainly used in the ambient environment, and very little is available [58]. This can explain why total phosphorus was found below the standard limit at all sampling locations and periods. Phosphorus is used as a fertilizer in agriculture along river systems and is relatively immobile in the soil. The uptake of phosphorus by biota increases the phosphorus storage capacity in the application area [59]. However, elevated concentrations of $NO_3^-$ and $PO_4^{3-}$ can have detrimental effects on aquatic organisms as it may lead to depleted oxygen levels and prompt eutrophication [60]. The mid-lower reaches of the river had notable total $SO_4^{2-}$ concentrations, which may be related to the usage of sulfate-containing fertilizers in the farming operations in this zone. According to Moreno and coworkers [61], sulfate tends to accumulate in the bottom sediments and flow downwards the water column, potentially explaining the high sulfate concentrations recorded at the sampling sites (S24-S25; Table S4) of the study area, thus, acting as a sink.

While analyzing Rachiine River quality, we compared our findings against Lebanese regulations and standards set by the Lebanese Standards Institution (LIBNOR). Specifically, we referred to LIBNOR standards for key water quality indicators such as BOD, COD, TDS, and microbiological parameters, including coliform bacteria counts [62]. Our results showed varying degrees of compliance with these national standards. In particular, the microbiological analysis indicated elevated levels of coliform bacteria in certain areas (S5→S25), suggesting potential contamination sources that exceed LIBNOR limits for safe water (<1 CFU/100 mL). While some parameters aligned closely with global recommendations, others, particularly microbiological aspects, exhibited significant deviations, underscoring the need for enhanced local water management practices and alignment with international best practices.

### 3.2. *Microbial analysis of water samples*

Results for mean values of the microbial indicator loads at the 25 different sampling sites are presented in Table 2. A significant difference in bacterial load was observed between the different sampling sites. This finding may be explained by the disparity of waste product disposal released into the river either directly or indirectly, mainly by neighboring communities. This study has shown a high bacterial load, which generally increases from the river's source to the downstream sites (Table S5). Fecal pollution was not surprising

**Table 4**
Analysis of variance (ANOVA) of the water physicochemical and microbial parameters over the sampling periods.

| Parameters | | Season | | | ANOVA for repeated measurements | | |
|---|---|---|---|---|---|---|---|
| | | October | January | April | F test | Wilks' Lambda | p-value |
| pH | July | 0.154 | **0.021** | 0.166 | 5.787 | 0.559 | 0.004 |
| | October | | 1.000 | 1.000 | | | |
| | January | | | 1.000 | | | |
| BOD | July | **0.000** | 1.000 | 0.082 | 13.357 | 0.354 | 0.000 |
| | October | | **0.000** | 0.284 | | | |
| | January | | | 0.228 | | | |
| EC | July | **0.000** | 0.520 | **0.007** | 63.772 | 0.103 | 0.000 |
| | October | | **0.000** | **0.000** | | | |
| | January | | | **0.000** | | | |
| TDS | July | **0.000** | 0.520 | **0.000** | 62.553 | 0.105 | 0.000 |
| | October | | **0.000** | **0.000** | | | |
| | January | | | **0.000** | | | |
| COD | July | **0.000** | 1.000 | 0.081 | 13.360 | 0.354 | 0.000 |
| | October | | **0.000** | 0.290 | | | |
| | January | | | 0.227 | | | |
| TEM | July | **0.000** | **0.000** | **0.000** | 284.719 | 0.025 | 0.000 |
| | October | | **0.000** | **0.000** | | | |
| | January | | | **0.000** | | | |
| Turbidity | July | **0.005** | 0.110 | 0.109 | 5.091 | 0.590 | 0.008 |
| | October | | 1.000 | 1.000 | | | |
| | January | | | 1.000 | | | |
| $NO_3^-$ | July | **0.006** | 0.063 | **0.001** | 13.651 | 0.349 | 0.000 |
| | October | | **0.001** | **0.000** | | | |
| | January | | | 0.024 | | | |
| $SO_4^{2-}$ | July | **0.000** | 1.000 | **0.000** | 53.710 | 0.120 | 0.000 |
| | October | | **0.000** | **0.000** | | | |
| | January | | | **0.013** | | | |
| $PO_4^{3-}$ | July | **0.000** | 0.201 | 0.47 | 7.098 | 0.508 | 0.002 |
| | October | | **0.001** | **0.000** | | | |
| | January | | | 1.000 | | | |
| TC | July | 0.055 | 0.252 | 0.125 | 0.620 | 4.490 | 0.013 |
| | October | | 0.115 | **0.035** | | | |
| | January | | | **0.006** | | | |
| *E. coli* | July | 0.051 | 0.249 | 0.633 | 0.850 | 1.295 | 0.301 |
| | October | | 0.053 | 0.068 | | | |
| | January | | | 0.930 | | | |
| ENT | July | 0.095 | 0.097 | 0.061 | 0.255 | 2.516 | 0.085 |
| | October | | 0.081 | 0.069 | | | |
| | January | | | 0.313 | | | |
| FC | July | **0.004** | 0.524 | 0.367 | 0.658 | 3.814 | 0.024 |
| | October | | **0.005** | **0.003** | | | |
| | January | | | 0.282 | | | |

since wastewater in Lebanon is discharged in the aquatic environment without any treatment [63]. Moreover, the increasing bacterial load downstream the river could be attributed to urbanization coupled with dysfunctional wastewater treatment plants [9]. Fecal pollution in surface water can originate from various sources, including agricultural practices and urban sewage. Due to the expensive nature of industrial fertilizers, market gardeners often rely on substantial amounts of animal manure as a cost-effective soil fertilizer [64]. Unfortunately, these practices can lead to the contamination of water bodies. The high coliform counts in the water samples suggest the occurrence of fecal contamination. This result is in agreement with Merhabi et al. (2019) who reported high fecal bacterial loads in Kadisha River. Our findings also showed high levels of *E. coli* ranging between $6.9 \times 10^4 \pm 7.4 \times 10^4$ and $4.6 \times 10^5 \pm 1.1 \times 10^6$ CFU/100 mL. The detection of *E. coli* in water is a cause for concern, especially the strains harboring antibiotic resistance or virulence determinants genes such as *E. coli* O157:H7 and *E. coli* O104:H4 that have been widely recognized as a major risk to human health [65]. Furthermore, over several decades, high prevalence of extended-spectrum β-lactamases (ESBLs) has been reported in recreational waters, wastewater, and surface water [66]. Of note, a recent study reported that 56 % of surface water samples were positive for ESBL-producing *E. coli* in surface water of North Lebanon [67].

### *3.3. Physicochemical properties of sediment samples*

Results of the physicochemical analysis are presented in Table 3. The average pH of the bottom sediments was recorded as 6.9. This finding aligns with the pH range typically observed in lakes that falls between 4 and 9 [68]. Furthermore, the average pH of sediments' river was slightly acidic, indicating the presence of additives and nutrients in the soil. However, the differences in pH observed were not significant enough to indicate land use patterns in the catchment [69]. The average EC value for the bottom sediments in the river was 0.35 mS/cm [70]. EC values in natural waters are usually within the range of 0.05–0.5 mS/cm, while highly mineralized waters can reach values as high as 1 mS/cm. Therefore, considering the mean EC of sediment samples, it can be concluded that the river experiences moderate anthropogenic pressure [71].

The interface between sediment and water plays a crucial role in various processes within different water bodies [22]. This region is susceptible to the deposition of organic material from external (allochthonous) and internal (autochthonous) sources. The accumulation of organic matter (OM) in sediments follows a periodic pattern until it reaches a steady-state condition, which depends on the rates of accumulation and sedimentation. The mean organic matter content in the river was found to be 4.6 % (Table 3). Organic matter (OM) levels in soils generally range from 2 % to 7 % [72], yet sandy sediments mainly contain lower organic matter, normally below 2 % [73]. Sediments with OM content over 1 % are classified as organically rich [74]. Based on this classification, the bottom sediments in the Rachiine River can be described as organically rich. OM can originate from agricultural activities [75] as well as urban runoff [76]. The decomposition of OM leads to increased level of carbon content in sediments [77]. In result, organic carbon (OC) and OM in sediments are essential ecological indicators of land use [69].

On another note, bottom sediments contained 0.28 % nitrogen, and 94 mg/L phosphorus in average. Matej-Łukowicz and colleagues [78] reported that these values prove the presence of macronutrients mainly found in commercial fertilizers, and inferring that it indicates an increased human activity in the catchment area [79]. These nutrients can also be found in domestic and urban waste in surrounding towns, and in agricultural runoff containing pollutants such as fertilizers and pesticides. This study also showed that nutrient concentrations in sediments increased along the water flow direction (Table S6). This could be attributed to hydrodynamic processes within the river during flooding season, as most nutrients accumulate in the topsoil which consists of finely grained particles vulnerable to erosion by surface runoff [80]. On the other hand, phosphorous content, mainly derived from inorganic sources like phosphorous-containing fertilizers, is relatively low compared to organic sources [70]. Unlike nitrogen, phosphorus does not exist in a gaseous state and consequently accumulates in bottom sediments, where it is released gradually into water through organic matter oxidation [81].

### 3.4. Heavy metals concentration in water and sediment samples

The levels of HMs in water at different sampling sites along Rachiine River are presented in Table S7. The data suggests that the HMs levels in water samples are within the acceptable range set by international standards [5]. The mean and maximum values for arsenic, copper, and lead were all at or below the detection limit. Moreover, the values for cadmium and chromium were slightly higher, yet within the acceptable limits. In addition, the data also revealed that the HMs parameters do not vary significantly between seasons, except zinc (Table 1). The values for arsenic were the highest during January, indicating a possible seasonal variation. Factors such as increased runoff from urban areas or agricultural fields during periods of high precipitation, or changes in temperature affecting the release of metals from sediments, could contribute to the observed seasonal fluctuations [82]. Seasonal variations in heavy metal levels could influence the accumulation of metals in aquatic organisms, with potential implications for food web dynamics and ecosystem functioning [83]. However, the values were still within the acceptable limits of WHO.

Table 3 presents the average concentrations of investigated HMs occurring in the sediments collected from the different sampling sites over the different sampling periods. Low levels of HMs were recorded suggesting that they originate from natural sources [84]. The concentration of HMs across all sampling sites was found to be within the permissible range for domestic water use (Table S8). This suggests that heavy metal contamination during the study period was not a major concern. However, this contradicts studies conducted in Lebanon that showed sediments contamination by HMs in the Upper Litani River Basin and Lebanese coastal zones [85,86]. Haydar et al. (2022) studied the Upper Litani River Basin and concluded that sediments in this region showed high concentrations of different heavy metals, which includes lead (Pb), cadmium (Cd), and mercury (Hg). These findings suggested a highly spread contamination mainly caused by industrial waste, agricultural runoff, and domestic discharges. Similarly, Merhaby et al. (2018) led investigations at the Lebanese coastal zones and detected high levels of heavy metals in marine sediments. This study showed that urban runoff, sewage discharge, and maritime activities were the primary sources of contamination. Interestingly, the findings of our study did not corroborate these studies where levels of heavy metal contamination in the sediments of Rachiine River were not comparable. Several factors could have contributed to the observed discrepancy such as sampling locations, sampling time, and variations in experimental methodology. Heavy metals contamination in Rachiine River was influenced by spatial and temporal variations. Further in-depth studies should be conducted to better assess the dynamics and evaluate currently enforced environmental protection measures.

### 3.5. Spatiotemporal variation in water quality

Analysis of spatiotemporal variations is essential to evaluate the impact of various environmental factors on water quality and direct resource management strategies. Such variations are often studied using Analysis of Variance (ANOVA) as a statistical tool to assess the significance of experimental data obtained from different locations over a specified period of time [87]. As such, statistical analysis using ANOVA was performed in the current study to test the differences among the sampling sites, and results are summarized in Table 4. Significant differences were observed among parameters for samples collected over different seasons ($p < 0.05$). Natural variabilities and anthropogenic factors, including agricultural and industrial activities, may have contributed to the observed differences in samples collected over different periods. This implies that seasonal variations in the examined parameters should be taken into consideration when evaluating water quality in monitoring programs [88]. The observed spatiotemporal variations in water quality parameters supported the complementarity between natural and anthropogenic factors in influencing the quality of aquatic ecosystems (Li et al., 2024). Furthermore, the findings of our study present important inferences for water resources management and environmental policy development, where future water quality changes can be anticipated from the established temporal trends which can aid in adapting management strategies to mitigate potential impacts [89].

### 3.6. Principal components analysis

Principle component analysis (PCA) is an important statistical tool that has been applied to conduct comprehensive water quality assessments and identify potential sources of pollution and their apportionments [45]. Prior to the analysis, the suitability of the data was evaluated using Bartlett's test and the KMO measure. Bartlett and KMO analyzes were $p = 0.00$ ($<0.001$) and 0.865 ($>0.5$) for water samples parameters, and $p = 0.00$ ($<0.001$) and 0.877 ($>0.5$) for soil samples parameters (Table S9), indicating data adequacy for PCA [45]. Based on One-Sample Kolmogorov-Smirnov normality test, many variables are not normally distributed. However, PCA does not require variables to be normally distributed (Tables S10–S11). The rotated component matrix statistics identified four principal components (PCs) with eigenvalues exceeding 1 (Fig. 2). The highest ranked component PC1 explained 64.344 % of the total variance in the data and consisted mainly of physiochemical parameters such as $SO_4^{2-}$ ($r = 0.984$), EC ($r = 0.959$), and TDS ($r = 0.958$). This component likely represents general water quality characteristics related to the mineral content and ionic composition. It is noteworthy that soluble salts contributing to PC1 are naturally derived from the geological composition of the basin's rock and soil structure, and spreading from these original sources. The strong correlation with TDS, a major contributor to turbidity, validates the significance of this PC [90]. According to PC1, it can be concluded that the river water quality is highly influenced by erosion and surface flows [45].

The second PC accounted for 11.438 % of the variance and showed positive correlations with $PO_4^{3-}$, BOD, COD, TC and *E. coli*, and a negative correlation with arsenic. Thus, fecal pollution in surface water primarily originates from human and animal sources, both through point sources and non-point emission sources [85]. In Lebanon, the main point sources of TC and *E. coli* are domestic sewage, since around 58 % of buildings are connected to sewerage system, while the rest discharged the untreated wastewater into water bodies [28]. Moreover, non-point sources of fecal pollution include contaminated surface runoff and leaching from the soil, mainly originated from grazing livestock feces and cattle manure in cultivated areas [91].

PC3 showed positive correlations with $NO_3^-$, ENT, and turbidity. Additionally, moderately positive and negative correlations with PC3 were observed between pH and chromium, respectively. Nitrate fertilizers are frequently applied in agricultural practices, leading to the introduction of nutrients into streams through runoff from both domestic wastewater and agricultural land. Given the urban plain nature of the Rachiine River, it can be suggested that PC3 is directly influenced by agricultural activities and domestic waste discharge. Furthermore, the negative contribution of BOD to this PC may result from the oxygen consumption required for organic matter decomposition [90]. The last component PC4 is primarily influenced by BOD and *E. coli* which showed positive correlations. On

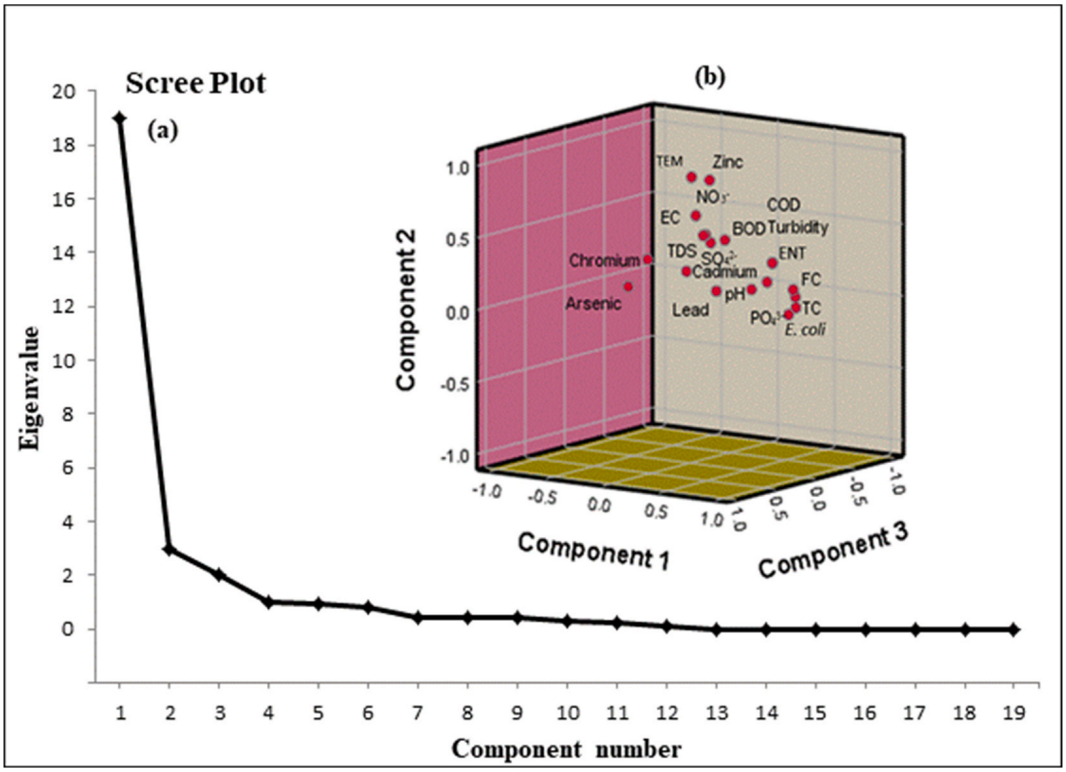


**Fig. 2.** PCA of measured physiochemical, heavy metals and biological parameters in water samples by (a) scree plot of the characteristic roots (Eigen values) and (b) component plot in rotated space.

the other hand, temperature and arsenic were negatively correlated with PC4. Interestingly, high values of BOD highlight the organic pollution index derived from human and animal feces and waste [92].

Fig. 3 shows the principal component profile of physicochemical and HMs parameters of the river's sediments at different sampling sites. PCA resulted in five PCs which explained 37.600, 14.558, 13.397, 8.386 and 7.749 % of the data set variance, respectively. The cumulative variance showed that the first three principal components combined explain 65.556 % of the total variance, and the first five components explain 81.690 %. It is evident that the first three PCs capture the majority variance in the dataset, suggesting a potential dimensionality reduction by considering only these PCs. Overall, PC1 showed high loadings of TN, OM, and TP. Fertilizers, herbicides and pesticides release huge amounts of nitrate and phosphate [93]. Organic matter in sediments acts as a reservoir for nutrients [94]. Accordingly, it can be concluded that PC1 is directly influenced by agricultural activities and domestic and urban waste from the nearby towns [95].

Furthermore, arsenic, cadmium, and lead had higher factor loadings in the first factor, which can be interpreted as pollution load. The variables chromium and zinc load more strongly on the second factor, which may represent geogenic sources. The third factor is dominated by copper, which may be related to the natural mineralization of copper in soil. Heavy metals contamination can originate from various sources including the usage of inorganic fertilizers and livestock manure in agricultural activities, as well as the irresponsible combustion of coal, wood, and plastic-based products in brick kilns for the generation of energy [96].

While PCA is useful in identifying key parameters that impact water and sediment quality and assessing the efficiency of water treatment processes, its results are highly influenced by the specific data sets under investigation and type of analysis applied, and therefore may vary among different studies and situations. Hence, larger data sets and various types of statistical analyses become essential to better correlate these parameters and their impact on water quality.

### 3.7. Cluster analysis

Cluster analysis has been a fundamental statistical tool for effective environmental monitoring and management [97]. The impact of spatial variations on water quality was evaluated by constructing a complete linkage hierarchical clustering dendrogram. Sampling sites were clustered based on similarity of responses to multiple variables. Each cluster encompassed distinct environmental conditions, specific land use practices, and anthropogenic stimuli that can potentially influence the quality of water and sediment. This

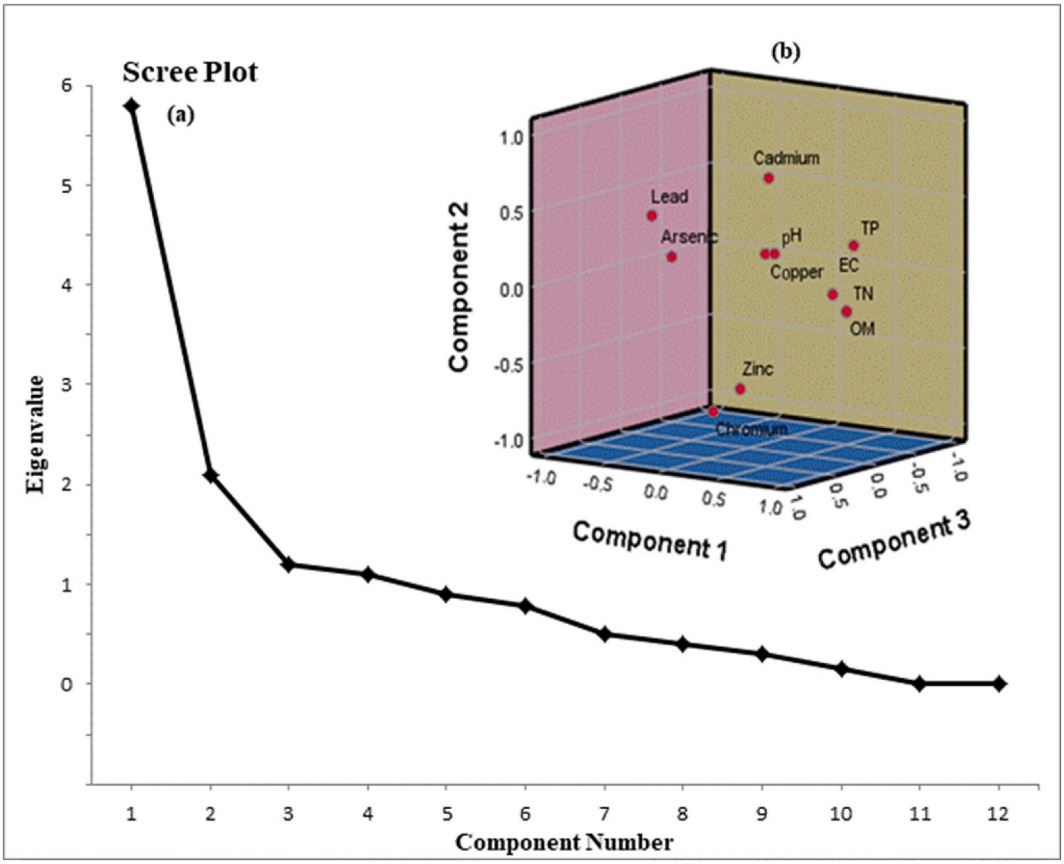


**Fig. 3.** PCA of measured physiochemical parameters and heavy metals level of the river's sediments by (a) scree plot of the characteristic roots (Eigen values) and (b) component plot in rotated space.

information will be particularly valuable in developing management policies such as tailored monitoring programs, and the implementation of measures for pollution control and land use.

In the current study, the cluster membership showed strong associations among the sampling sites that may be impacted by common sources of pollution. The computed dendogram (Fig. 4) grouped all the sampling sites into three statistically important clusters, thus providing a useful and reliable classification of the river. Cluster 1 consisted of 5 sample sites and corresponded to 20 % of the total sampling sites. Cluster 2 contained 9 sample sites whereas cluster 3 grouped 11 sites. The percentages attributed to cluster 2 and 3 were 36 % and 44 %, respectively, with respect to the total sampling sites. Cluster 1 represented the modest deviation in the chemical and microbial components of water and sediments.

According to this cluster, it can be inferred that the concentrations of pollutants were generally lower at sites S1-S5 compared to the other sites under study, indicating lower levels of pollution in the upstream area. On the other hand, the samples positioned in the cluster 2 and 3 were mostly affected by anthropogenic activities such as sediment dredging, waste from industry, farming, olive presses and sewage from upstream. Group 2 was mainly distributed in the middle reaches whereas group 3 represented the lower reaches. In these sampling sites, the river passes through residential areas, farmland, industries and hospitals. This infers that there is a significant difference between the upstream, the middle and downstream. The notable increase in pollution observed in the middle and downstream areas can be attributed to local sources of pollution, such as surface runoff, inadequate farming practices, sand mining, and anthropogenic land use zones.

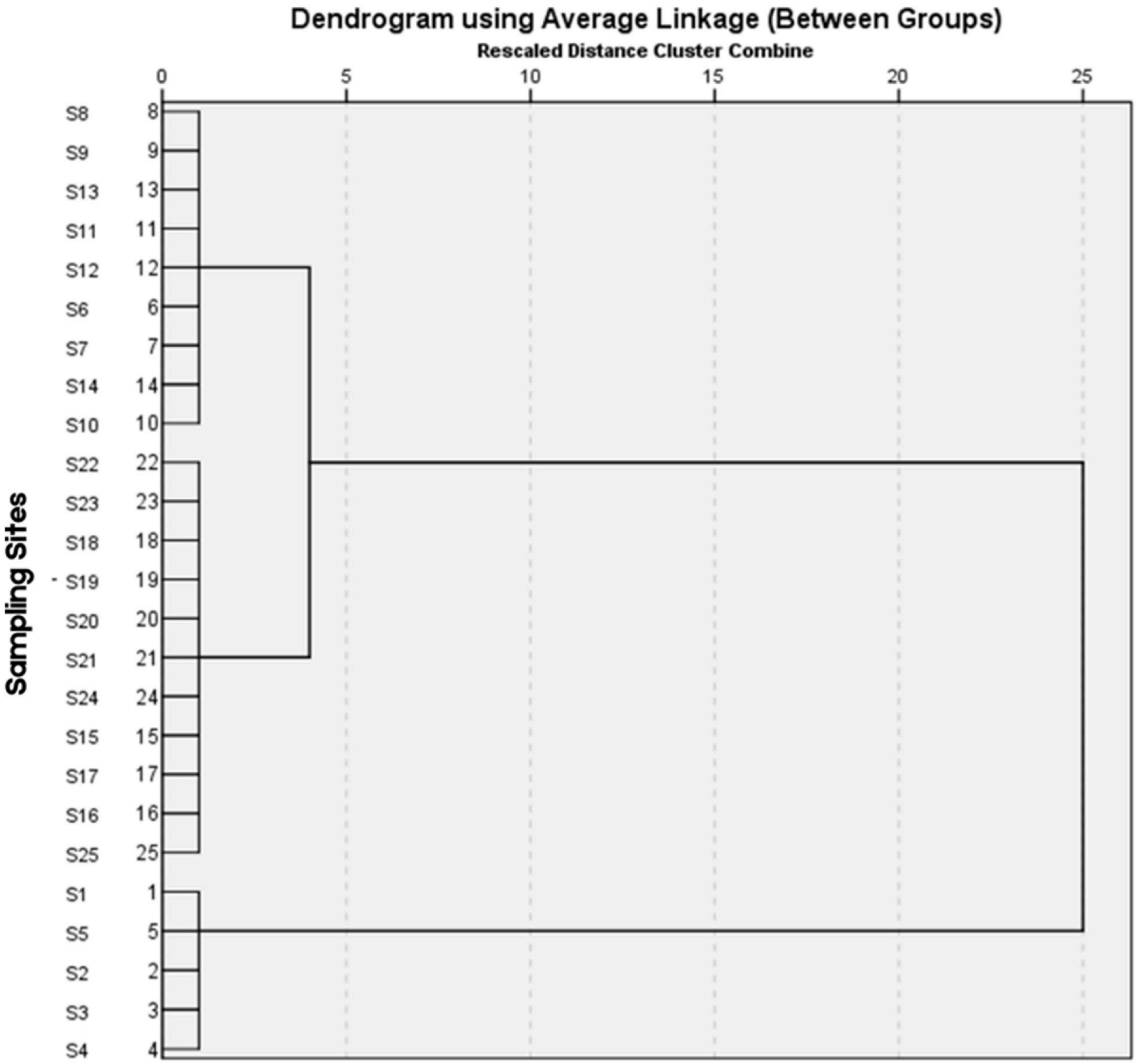


**Fig. 4.** Dendrogram showing clustering of sampling stations of the river during the sampling period.

Thus, cluster analysis facilitated the identification of spatially cohesive groups of sampling sites exhibiting similar quality characteristics. Each identified cluster encapsulated distinct environmental conditions, land use practices, and anthropogenic influences that contribute to variations in water and sediment quality. This will provide valuable insights to guide management decisions and policy development, such as targeted monitoring programs, pollution control measures, and land use planning initiatives.

In summary, while Rachiine River does exhibit some contamination, particularly from local agricultural and urban activities, it is generally less polluted than many of the world's major rivers. Recent studies on rivers in Lebanon showed that many rivers in Lebanon are significantly contaminated with fecal indicator bacteria [98]. For instance, the Ras El-Ain Natural Ponds in Tyre (Southern Lebanon) and Kesserwan mineral water (Mount Lebanon) have been assessed for water quality, revealing moderate to high contamination levels from urban activities and agricultural runoff, similar to those affecting the Rachiine River [99,100]. Similarly, rivers in Turkey and Tunisia face substantial pollution, primarily from industrial activities and agricultural inputs, contributing to its deteriorating water quality [45,101]. In contrast, water bodies in Arabian Gulf have shown varying levels of pollution due to rapid urbanization and industrial activities, requiring strict water management practices [102,103]. In Europe, despite stringent environmental regulations, rivers continue to experience significant pollution due to urbanization and agricultural practices [104–106]. In many developing countries, rivers are increasingly polluted as a result of rapid industrialization and inadequate waste management systems, exacerbating environmental and public health risks [107]. Therefore, continued monitoring and management of Rachiine River are essential to prevent further degradation, especially as regional development increases. Our analysis revealed a positive correlation between microbial contaminants and nutrient levels suggesting that nutrient-rich environments, often resulting from agricultural runoff or wastewater discharge, may promote microbial growth, contributing to the degradation of water quality and posing health risks. On another note, the high nutrient levels disturb the natural degradation of organic pollutants, leading to their accumulation in the water column. This accumulation can further impact aquatic life, increasing the risk of eutrophication and hypoxia, which are detrimental to the river's ecological balance. These findings underscore the importance of considering both microbial and chemical contaminants in water quality management, of Rachiine River and similar ecosystems, and the need for integrated approaches that address the sources of both types of contaminants, particularly in regions where agricultural runoff and industrial discharges are prevalent.

Our findings are significant not only locally but also globally, as water pollution is a pressing issue affecting rivers and freshwater systems worldwide. By comparing the pollution levels and seasonal dynamics of Rachiine River to global trends, our research contributes to a broader understanding of how similar factors impact riverine environments across different regions. The methodologies employed in this study are adaptable and can be applied to other rivers globally, making the findings relevant for international efforts aimed at improving water quality management. Furthermore, this research adds valuable data from the Middle East, a region where comprehensive pollution studies are relatively scarce, thus filling a critical gap in global water quality assessments.

## 4. Conclusions

This study provided a comprehensive assessment of the chemical and microbial pollution of water and sediments in Rachiine River in Northern Lebanon. Multivariate analysis provided notable spatial variations in physicochemical parameters across different sites of the river basin, mainly influenced by anthropogenic activities, urbanization, industrial effluents, and agricultural runoff. Bacteriological analysis exhibited the presence of coliforms and fecal enterococci that indicate severe contamination of the river as well as alarming incompliance with recreational use and irrigation standards. On the other hand, the study showed the presence of heavy metals, organic pollutants, and microbial pathogens at different levels across different sampling sites; this highlights the urgent need for strict strategies to enforce environmental management measures to protect water resources and equally human health. Furthermore, this study revealed the dynamic nature of river ecosystems and highlighted the importance of continuous monitoring and abidance by management practices put in place. Mitigating the detrimental effects of pollution can be performed by the co-existence of scientific researches and practical conservation efforts to ensure sustainability of aquatic ecosystems for future generations and preserve river's water used for irrigation and protect the coastal area receiving this water. In addition, the results advise sustained monitoring and implementation for extended period along through wholesome health assessments among local residents, to analyze the magnitude of the long-term impact of fecal contamination on public health. Future research should focus on identifying specific sources of microbial contamination within the catchment area and assessing their impacts on water quality. Longitudinal studies are also necessary to monitor changes in water quality over time, particularly in response to regulatory measures or environmental changes. Additionally, expanding the scope of research to include a wider range of pollutants and emerging contaminants, such as microplastics and pharmaceuticals, will provide a more detailed understanding of water quality issues. While the methodologies applied in this study are versatile and can be applied to rivers worldwide, the findings may not be universally applicable to rivers in other climate zones or with different land uses. For instance, rivers subject to intensive agricultural or industrial activities may exhibit distinct water quality profiles. Therefore, caution should be exercised when applying these results to other contexts. Future research should consider conducting comparative studies across different climate zones and land-use types to assess the broader applicability of the findings and develop tailored water quality management strategies for diverse environments.

## Data availability

The authors declare that the data supporting the findings of this study are available within the paper and supplementary file.

## CRediT authorship contribution statement

**Rosette Mansour:** Writing – original draft, Methodology, Formal analysis, Conceptualization. **Jalal Halwani:** Validation, Formal analysis. **Mohammad H. El-Dakdouki:** Writing – review & editing, Visualization, Supervision, Project administration. **Sara Mina:** Writing – review & editing, Supervision, Investigation.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e39016.

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