

Evaluation of Physicochemical Parameters, Heavy Metal Contamination and Related Health Risks in Bangladesh's Dhaleshwari River

Habiba Akther^a; Md. Rakibul Hassan^a; *Md. Habibur Rahman Habib^{a,b};
Mohtasim Ahmed^a

^aDepartment of Environmental Science and Engineering, Jatiya Kabi Kazi Nazrul Islam University, Mymensingh, Bangladesh

^bDepartment of Oceanography, University of Dhaka, Dhaka, Bangladesh

Corresponding Author: **Md. Habibur Rahman Habib**

Abstract: This study investigated the physicochemical parameters (pH, Temperature, DO, ORP, TDS and EC) of water quality along with the 12 heavy metals concentrations in the Dhaleshwari River. DO and EC concentration indicated the presence of impurities and higher salt content in the water respectively. Various water quality indices were applied to evaluate environmental and human health risks. The average value of Nemerow's pollution index (P_N) was found to be 41.2, indicated river water seriously polluted. Metal Index (MI) indicated threshold warning of river water for drinking purpose. Average HPI and HEI were found to be 136.5 ($HPI > 100$) and 28.96 ($HEI > 20$), respectively, which indicated river water quality is not suitable for irrigation purposes. Average PLI value was found to be 1.77 ($PLI > 1$), revealed that river water quality moderately polluted for aquatic life. According to CCME (Canadian Council of Ministers of the Environment) standard, the mean ERI was found to be 1109.3, which indicated higher ecological risk in Dhaleshwari River. Toxic metal sources in water were located using source identification techniques such as principal component analysis (PCA), correlation analysis (CA). According to the total Heavy Metal Toxicity Load (HMTL), 64.35%, 56.34%, 78.73%, 99.82%, 87.4% and 86.87% of As, Cd, Co, Cr, Mn, and Pb should be removed from the surface water to ensure safety. There were a threat of health risks resulting from the exposure through dermal contact, with As, Cd, Cr, Mn, Pb, Z, and V being the main contributors. The orders of decreasing values of the mean HQ were $Cr > Mn > V > Cd > As > Pb$ via dermal contact for both adults and children. The mean HQ for only chromium concentration poses substantial risks to both adults (66.05) and children (62.37) when consumed orally ($HQ > 1$). The study demonstrated how human sources affect the amount of pollution in river water.

Keywords: Toxicity, Heavy metals, Health risks, Dhaleshwari River, Bangladesh

1. Introduction

Water is an abundant resource throughout the entire world. Among the most significant and well-known surface water resources are rivers (Hasan et al., 2020). Rivers play an important role in the hydrologic cycle, having an enormous effect on the Earth's surface features and functioning as important regulators for the survival of several creatures. Furthermore, they are fundamental to the continued maintenance of a healthy water cycle and ecological system. A large number of industries were constructed adjacent to river banks (Uddin and Jeong, 2021). A considerable number of industries discharge untreated or insufficiently treated industrial effluents into the nearby surface water environment as a result of deficiencies in law enforcement and poor monitoring, particularly in developing nations. This practice eventually leads to a deterioration in the overall quality of the water body by introducing a variety of water contaminants, including toxic heavy metals (Ali et al., 2018; Edokpayi et al., 2017; Proshad et al., 2021). Heavy metals are a group of metals or metalloids that have a density above 5 g/cm³ (Jaishankar et al., 2014). Heavy metals are considered environmental contaminants due to their toxicity, long-term persistence in the environment, and bioaccumulation (Hossen and Mostafa, 2023; M. S. Islam et al., 2023; Monira et al., 2023). Cr, Ni, Cu, Zn, As, Pb, Hg, and Cd are the most toxic heavy metals and metalloids found in the environment (Ali et al., 2022; Hossen and Mostafa, 2023). It has been determined that surface water contamination by heavy metals poses a serious environmental risk. Water is regarded to be the "lifeblood of the biosphere" (Kubra et al., 2022). However, this lifeblood of the biosphere is endangered by both inorganic and organic pollutants, and water is a universal solvent that dissolves these pollutants (Hossen and Mostafa, 2023). Heavy metals are the most detrimental pollutants in riverine ecosystems, continually causing harm to the entire ecological system (Hossain et al., 2021; M. S. Islam et al., 2023; Proshad et al., 2021). Heavy metals' dissolution, precipitation, and sorption behavior can change during movement in the riverine system, influencing their function, bioavailability, and eco-toxicity (Haque et al., 2022; M. S. Islam et al., 2023). Growing urbanization, industrialization, technological advancement, and risky farming practices are all contributing to the rise of heavy metal pollution in the aquatic ecosystems of emerging nations, especially Bangladesh (Hossain et al., 2021; Rakib et al., 2022). Bangladesh's economy has always relied on the tannery sector. It is important to consider that these industries are among the most environmentally detrimental sectors, as they have a substantial adverse effect on the environment (Safiur Rahman et al., 2021). Chrome tanning is a widely employed method in approximately 80 to 90% of leather manufacturing processes. A significant quantity of chromium (Cr) is disposed away together with the wastewater during the chrome tanning process. Subsequently, after being processed, these chemicals are dumped into a river, pond, or open space. Chromium (Cr) is a toxic and cancer-causing heavy metal primarily released by tannery industries. Research findings

indicate that the level of Cr contamination in Bangladesh is of utmost importance. Cr is a vigorous oxidizing agent characterized by its corrosive and oxidizing properties, making it very toxic. It finds extensive application in corrosion control, tanning, plating, and pigment synthesis (Hossain et al., 2021; Safiur Rahman et al., 2021). In addition, prolonged exposure to and/or ingestion of chromium components in riverine environments over time can lead to various human diseases such as allergy, lung cancer, high blood pressure, heart and kidney problems, respiratory tract infections, and vision loss (Hossain et al., 2021; Safiur Rahman et al., 2021). Furthermore, the introduction of these hazardous heavy metals into the human body can occur not only through the consumption of polluted water and/or aquatic species, but also through direct contact with the water through the skin (Saha and Paul, 2019). Previous research found that harmful materials enriched aquatic biota cause nephritis, kidney lesions, hypertension, liver damage, renal failure, and hepatic dysfunction in humans (Ali et al., 2022). Therefore, it is vital to measure the amounts of hazardous components in the aquatic compartment, such as water, to evaluate their levels of contamination and the potential for detrimental impacts on the riverine ecosystem in Bangladesh. The Wen-Rui Tang River in China contains a number of heavy metals, as reported by Qu et al. (2018). The following elements were measured: lead (Pb) at 30.1 mg/L, cadmium (Cd) at 16.0 mg/L, mercury (Hg) at 46.1 mg/L, copper (Cu) at 96.8 mg/L, zinc (Zn) at 98.3 mg/L, arsenic (As) at 1.71 mg/L, and chromium (Cr) at 7.7 mg/L. The main industries found to be the source of these heavy metals in the river were found to be the leather tanning and electroplating sectors (Qu et al., 2018). Twelve metals were investigated by Huang et al. (2021) in the southern Chinese Xiangjiang River. Analyzing the toxicity load, risk assessment, and pollution features related to these heavy metals was the primary goal (Huang et al., 2021). In order to better understand how human activity affects water chemistry and the ecological danger that results, Ubuoh et al. (2023) studied the Nworie inland river in Imo State, Nigeria. This suggests that over time, there has been a rise in both the amount of organic waste deposited into the river and human activity (Ubuoh et al., 2023). Environmental quality indicators and pollution indices are effective methods for processing, analyzing, and presenting unfiltered environmental data to decision-makers, managers, technicians, or consumers (Kumar et al., 2020, 2018). Numerous studies has been undertaken to investigate the presence of heavy metals in the river water of Bangladesh, specifically focusing on the Buriganga River. Buriganga is referred to as a "dead river" due to the poor water quality. The water reveals an intense black hue reminiscent of burned Mobil during the summer season (Hossain et al., 2021; Rampley et al., 2020; Uddin and Jeong, 2021). It is widely acknowledged that the largest tannery industries, previously located in Hazaribagh, old Dhaka, have recently been relocated to Savar Upazila . The residents of the Savar Tannery Industrial Park area have already expressed their dissatisfaction with the deteriorating condition of the river water in Dhaleshwari.

Additionally, there have been reports in the media highlighting issues such as the malfunctioning of the CETP (Central Effluent Treatment Plant) and the presence of illegal outlets that bypass the main CETP line. The tannery industries use an extensive number of chemicals during the tanning process, which are widely acknowledged as significant sources of heavy metals in the environment and provide substantial environmental risks. Water quality assessment is an essential step in preserving the environment and public health (Haque et al., 2020). In order to reduce pollution levels, the first stage in this process is to assess the quality of the water and locate the sources of contamination. Existing assessment techniques, such as the ecological risk index (ERI) and hazard index (HI), cannot accurately estimate the percentage of toxic heavy metals needed to make contaminated water safe for human health (Proshad et al., 2021). The heavy metal toxicity load (HMTL), a novel technique created by Saha and Paul (2019), can precisely identify the concentration of dangerous heavy metals in water that may be harmful to human health (Saha and Paul, 2019). With this assessment method, the proportion of heavy metals that are harmful and must be eliminated from water bodies can be ascertained. A suitable toxicity impact on human health can be obtained from the hazard intensity score (HIS) of each heavy metal that is used to estimate HMTL in water (Saha and Paul, 2019). The Dhaleshwari River's strategic significance, particularly its closeness to the Savar Tannery Estate, is a significant source of heavy metals like chromium. Dhaleshwari is now only impacted by tannery effluent, unlike Buriganga or Turag, which makes it a crucial hotspot for the pollution of Cr, Pb, Cd, and Ni (Kubra et al., 2022; Proshad et al., 2021; Tisha et al., 2020). Prior Dhaleshwari's research has employed HPI, HEI, ERI, and PLI (A. S. S. Ahmed et al., 2021; Tisha et al., 2020), which assess the level of pollution but do not specify the amount of each metal that has to be eliminated in order to render the water safe. Heavy metal removal objectives for this river have not been quantified in any previous study, despite the fact that they are critically needed for environmental restoration planning and CETP optimization. This study fills a significant gap in the literature by examining the effects of tannery industries on the Dhaleshwari after relocation (Hasan et al., 2020; Monira et al., 2023).

2. Materials and Methods

2.1. Study area

The Dhaleshwari River is a tributary of the Jamuna River in the central part of Bangladesh. According to the intended goal, the study was conducted on the specified part of the Dhaleshwari River, starting from Dhamrai to Kadomtuli in the vicinity of the Savar Tannery estate, as shown in Fig. 1. The study area (Dhaleshwari River, Hemayetpur) is situated at the Savar Upazilla under Dhaka district, Bangladesh (Fig.1), which is located approximately 18 kilometers northeast of the significant tannery industrial regions (Hazaribagh Tanneries,

Dhaka city). The Dhaleshwari River is close to the tannery estate in Savar, Dhaka, Bangladesh. Its coordinates are latitude 23.8583°N and longitude 90.2667°E. Its total area is 280.13 km². The sampling stations were chosen based on the level of industrialization and the availability of waste disposal sites adjacent to the river banks. The point sources consist of several industrial sectors, including leather, textiles, and metal processing. The current study focused on the Savar tannery effluent along the Dhawleshari River and how it is damaging river water quality on a daily basis. Water samples were taken from ten separate sites along the river from this specific point. Table (S1) shows information about the sampling sites and distance from Savar tannery.

2.2 Collection and preparation of samples

Random sampling technique was used to gather river water samples from ten distinct stations (sampling sites) in the Dhaleshwari River (Table S1). The study was conducted in October 2023, just after the end of the monsoon season. 200 ml of water samples were taken from each sampling site using plastic bottles with double stoppers in order to track the Dhaleshwari River's water quality. The bottles underwent a thorough cleaning, rinsing, and overnight treatment with 5% nitric acid HNO₃ (Merck, Germany) before sampling. After using deionized water to clean them, the bottles were dried. The dried bottles were labeled with a unique serial number for every sampling site in order to distinguish the samples that were collected. The plastic vials were cleaned three times or more before sampling at each location. Surface water samples that had not been filtered were gathered in the middle of the river. In each polypropylene bottle, a few drops (2–3 mL) of ultrapure nitric acid were added to achieve a pH of ~1 before being transferred to the Central Laboratory of the Bangladesh Agricultural University, Mymensingh. After collecting, the bottles were securely capped. Bubble formation and suspended particles were strictly avoided while sampling. Water samples were collected from each station following EPA (1997) guidelines (USEPA, 2012). At the Central Laboratory of the Bangladesh Agricultural University, for the evaluation of heavy metals, the Inductively Coupled Plasma Mass Spectrometer (ICP-MS) method was used in this study. For this purpose, 100 mL of each water sample was initially filtered using 0.22 µm syringe polyvinylidene difluoride membrane filters and, to prevent further contamination, using Whatman No. 41 filter paper and stored in a container (freezer at 4°C) following the guidelines of APHA (2012) (Association, 1926) (Rice et al., 2012).

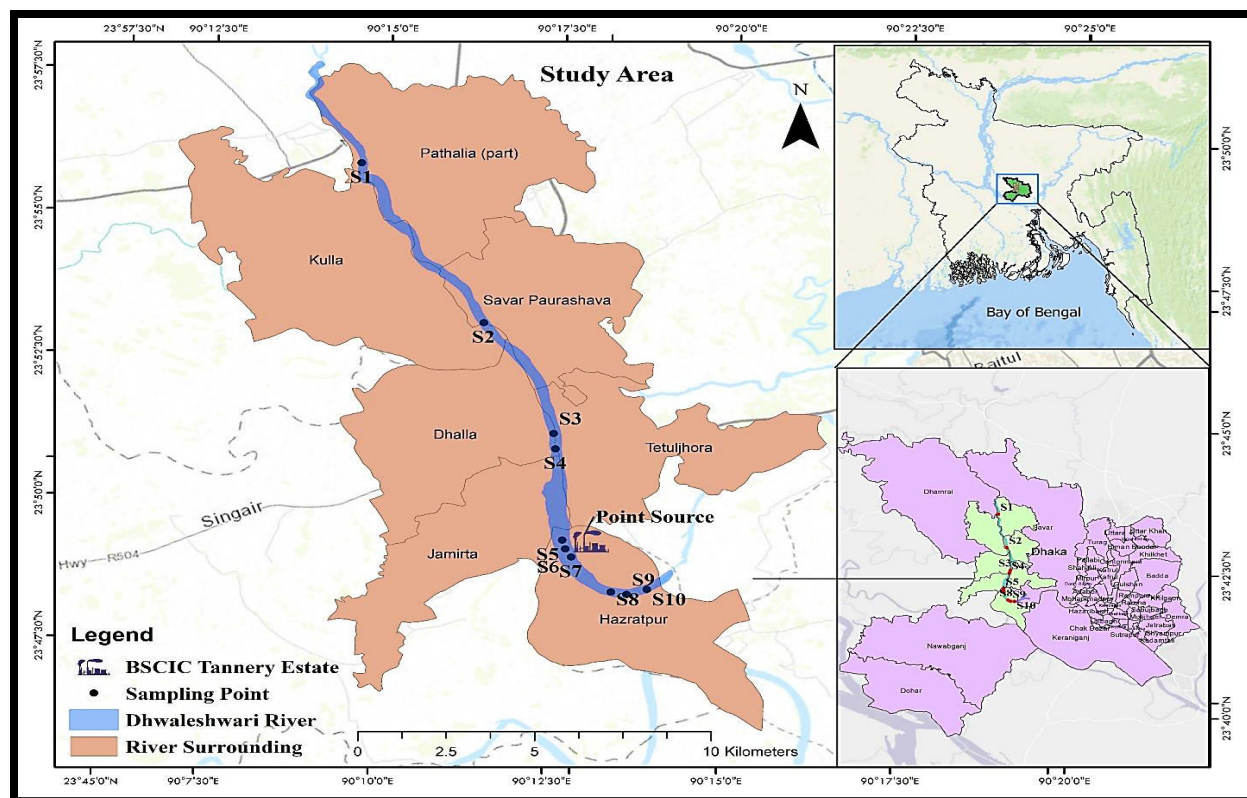


Fig. 1: Sampling sites in the Dhaleshwari River, Bangladesh

2.3 Analytical Methods

2.3.1 Physicochemical parameter analysis

On board of sample collection, physicochemical parameter analysis for dissolved oxygen (DO), oxidation reduction potential (ORP), pH, electrical conductivity (EC), total dissolved solids (TDS), and temperature was carried out with the help of the HANNA Multiparameter (Model: HI-98194) and the Hach HQ30D Portable Dissolved Oxygen Meter (Model: HQ30D53315000).

2.3.2 Heavy metal analysis

This study evaluated a total of 12 heavy metals, including As, Cd, Cr, Cu, Fe, Mn, Ni, Pb, Zn, Se, and V. The analysis of heavy metals was conducted with an Inductively Coupled Plasma Mass Spectrometer (Model: ICP-MS-2030LF, SHIMADZU) using at the Central Laboratory, Bangladesh Agricultural University, Mymensingh.

2.4 Assessment of heavy metal pollution in surface water

2.4.1 Heavy Metal Toxicity Load

The concept of heavy metal toxic load (HMTL) serves as a means to assess the level of treatment necessary for water to meet human safety standards while also assisting in

preserving evidence of efficient treatment and management strategies (Proshad et al., 2021). HMTL is calculated by multiplying the measured concentration of heavy metals by their hazard intensity, as indicated in Equation (1) (Huang et al., 2021).

$$HMTL = \sum_{i=1}^n C \times HIS \dots \dots \dots (1)$$

Where HIS, or the hazard intensity score, is derived from the Agency for Toxic Substances and Disease Registry and C, or the concentration of heavy metals in water, and n, or the number of heavy metals (ATSDR) (ATSDR, 2022; Registry, 2017).

2.4.2 Single-factor pollution Index

The present study used this technique to evaluate the level of pollution indicated by a specific contaminant in the samples of river water (Haque et al., 2020). The main contaminant that most affects the pollution levels at each sample location may be found using this method.

$$Pi = \frac{Ci}{Si} \dots \dots \dots (2)$$

Where Ci denotes the heavy metal concentration that has been measured, Si is the heavy metal standard value, and Pi is the single factor pollution index. When, $Pi > 1$, representing the content of the heavy metal exceeds the standard (Haque et al., 2020). The environmental quality standard assesses the single-factor pollution index technique's grading criterion (Table S2).

2.4.3 Nemerow's pollution index

This method is complete in assessing the level of pollution caused by several heavy metals at a sampling site. The calculation formula as follows:

$$PN = \sqrt{\frac{[(1/n) \sum (\frac{Ci}{Si})]^2 + [\max (Ci/Si)]^2}{2}} \dots \dots \dots (3)$$

Where Si denotes the heavy metal standard value, Ci is the measured concentration of the metal, and n is the number of indices. The NI is divided by six to determine the pollution level. There is no pollution at all at 0.5, clean at 5-7, warm at 0.7-1.0, polluted at 1.0-2.0, mild at 2.0-3.0, and severe at > 3.0 (Bodrud-Doza et al., 2019; Haque et al., 2020).

2.4.4 Metal Index (MI)

The Metal Index (MI) for river water evaluates the general quality of drinking water while accounting for the possible health effects of heavy metals. The metal index can be calculated using the following equation:

$$MI = \sum_{i=1}^n \frac{Ci}{(MAC)i} \dots \dots \dots (4)$$

Where C_i is each metal's mean concentration and MAC is its maximum permitted concentration. MI value > 1 represents threshold of warning (Caeiro et al., 2005). This current study evaluated river water quality using the Bangladesh drinking water quality standard (ECR'23) for calculating the metal index.

2.4.5 Heavy Metal Pollution Index

The heavy metal pollution index (HPI) is an indicator that can be applied to reduce surface water pollution. HPI was used to determine a rating or weightage (W_i) for each parameter (Haque et al., 2020; Hasan et al., 2020; Sahoo and Swain, 2020). The method developed by Edet and Offiong (2002) was used to determine the heavy metal pollution index (HPI) for water samples (Edet and Offiong, 2002).

$$HPI = \frac{\sum_{i=1}^n Q_i W_i}{\sum_{i=1}^n W_i} \dots \dots \dots (5)$$

Where n is the number of parameters taken into consideration, W_i is the i^{th} parameter's unit weight, and Q_i is the i^{th} parameter's sub-index. So the expression that determines the sub-index (Q_i) of the parameter is as follows:

$$Q_i = \sum_{i=1}^n \frac{\{M_i(-)I_i\}}{(S_i - I_i)} \times 100 \dots \dots \dots (6)$$

The values of the i^{th} parameter are as follows: S_i is the standard heavy metal value, I_i is the ideal value, and M_i is the monitored value in $\mu\text{g/L}$. This study utilized the USEPA Guideline of water quality standards to assess the quality of river water for irrigation purposes (USEPA, 2012). In general, an HPI score of 100 is regarded as 'Critical' and $HPI > 100$ indicates the threshold for dangerous contamination (Table S3) (Badeenezhad et al., 2023).

2.4.6 Heavy Metal Evaluation Index

According to scholars (Edet and Offiong, 2002; Haque et al., 2020; Prasanna et al., 2012; Sahoo and Swain, 2020), the heavy metal evaluation index is typically used to assess overall quality in water bodies with according to heavy metals and calculated using the following equation:

$$HEI = \sum_{i=1}^n H_c / H_{mac} \dots \dots \dots (7)$$

The values of the i^{th} parameter are as follows: H_c is the measured value of the i^{th} parameter, and H_{mac} is the maximum admissible concentration. In this study, this index was used to evaluate the river water quality for possible irrigation purposes. Three categories were created for the heavy metal assessment index level (Table S4) (Bodrud-Doza et al., 2019; Edet and Offiong, 2002).

2.4.7 Contamination Factor and Degree of Contamination

The Degree of Contamination (Cd) describes the level of pollution due to specific metals and provides an assessment of the overall impact of all metals. It is expressed as follows (Abdel-Satar et al., 2017; Hasan et al., 2020).

$$Cd = \sum_{i=1}^n Cfi \text{ and } Cfi = \frac{CAi}{CNI} - 1 \dots \dots \dots (8)$$

The values of the *i*th parameter are as follows: *Cfi* is the contamination factor, *CAi* is the monitored value, and *CNI* is the highest allowable value. As to Hakanson's (1980) categorization, a *Cd* value of less than 8 denotes low contamination, $8 \leq Cd \leq 16$ signifies moderate contamination, $16 \leq Cd \leq 32$ shows considerable contamination, and $32 < Cd$ denotes very high contamination (Hakanson, 1980).

2.4.8 Pollution Load Index

The pollution load index (PLI) is an index for total assessment of the degree of contamination in water, and it is described as the *n*th root of the metal contamination factor (*Cf*) multiplication for Heavy metals (Haque et al., 2022) and was calculated using the following equation:

$$PLI = \sqrt[n]{(Cf1 \times Cf2 \times Cf3 \dots \times Cfn) \dots \dots \dots (9)}$$

PLI values less than 1 indicate no pollution, while PLI values more than 1 indicate heavy metal pollution (Rakib et al., 2022).

2.4.9 Ecological Risk Index

The Ecological Risk Index (ERI) was developed to evaluate the ecological consequences of river water consumption, following the methods outlined in Equations (10 and 11) (Proshad et al., 2021; Taiwo et al., 2020).

$$ERI = \sum RI = \sum Ti \times PI \dots \dots \dots (10)$$

$$PI = \frac{Cs}{Cb} \dots \dots \dots (11)$$

In this case, *RI* is the potential ecological risk factor for each heavy metal, *Cb* is the similar background value, *Ti* is the toxic-response factor of heavy metals, and *Cs* is the concentration of heavy metals in the water sample. *PI* stands for pollution index. The toxic-response factor of each studied heavy metals are 10, 30, 2, 5, 5, 1, 2, 5, 1, and 5 for As, Cd, Cr, Cu, Co, Fe, V, Pb, Zn, Mn and Ni respectively (Islam et al., 2021; Proshad et al., 2021; Taiwo et al., 2020). This study conducted with CCME standard to assess the ecological risk level in river water. A score of ERI less than 150 indicates low ecological risk, 150 to 300 indicates moderate ecological risk, 300 to 600 indicates significant ecological risk, and ERI greater

than 600 indicates extremely high ecological risk (Islam et al., 2021; Proshad et al., 2021; Taiwo et al., 2020).

2.4.10 Human Health Risk Assessment

A health risk assessment is a comprehensive evaluation that examines the detrimental impact of environmental contaminants on human health. Human exposure to heavy metals (HMs) often occurs through drinking, skin contact, and breathing. The health risks of HMs can be assessed based on these three pathways (Jiang et al., 2020; Uddin and Alam, 2023; Xu et al., 2021). The estimation of non-carcinogenic human health risk was conducted using a hazard quotient (HQ) (USEPA 1989) (Uddin and Alam, 2023).

$$HQ = \frac{CDI}{RfD} \dots \dots \dots (12)$$

The term "CDI" refers to the chronic daily intake of heavy metals (mg/kg/day), whereas "RfD" is the reference dosage of HMs as recommended by the USEPA. Chronic daily intake (CDI) helps in calculating the daily impact on human health caused by heavy metal ingestion from contaminated water (Saha and Paul, 2019), as illustrated in the equation (13)

$$CDI = \frac{C \times IR \times EF \times ED}{BW \times AT} \dots \dots \dots (13)$$

Equation (13), The HMs concentration in water is expressed as C mg/L, and the water intake rate is expressed as IR in L/day, with a maximum of 3.53 L/day for adults and 1.0 L/day for children. USEPA 1989 states that the exposure frequency (EF) for both adults and children is 365 days per year, with the exposure duration (ED) being 70 years and 6 years for adults and children respectively. According to USEPA (1989), the average body weight (BW) is 50 kg for adults and 15 kg for children. Lastly, the average time is represented by AT. AT is equivalent to 365 times ED. The Equation (13) can be simplified into the following (Uddin and Alam, 2023):

$$CDI = \frac{C \times IR \times 365 \times ED}{BW \times ED \times 365} = \frac{C \times IR}{BW} \dots \dots \dots (14)$$

So, the equation of Hazard Quotient (non-carcinogenic) into following:

$$HQ = \frac{CDI}{RfD} = \frac{C \times IR}{BW \times RfD} \dots \dots \dots (15)$$

The primary route of exposure for heavy metals (HMs) present in drinking water sources is through ingestion and dermal contact. Therefore, this study conducted non-carcinogenic health risk assessments based on direct oral intake and dermal contact, resulting in an equation for both oral and dermal intake. All variables, except for the reference dose,

remain unchanged. The reference dose value for oral intake is denoted by RfD_o , but for dermal intake, it is represented by RfD_d . If the HQ estimates values are greater than one, there is a possibility of non-carcinogenic risk, but a value less than one indicates no possibility of non-carcinogenic risk (Al-Saleh and Abduljabbar, 2017; Uddin and Alam, 2023).

2.5 Statistical analysis for heavy metals in water

This study's multivariate analysis, which uses principal component analysis (PCA) to identify heavy metal sources, is a useful method (Dey et al., 2021; Hossain et al., 2020; Huang et al., 2021; Proshad et al., 2021; Tyagi and Sarma, 2021). The statistical variables of the Dhaleshwari river water quality dataset, such as the maximum, minimum, mean, and standard deviation, were interpreted using descriptive statistical analysis. The major metals contributing to the calculated indices were determined by calculating Pearson's correlation coefficient between the indices and heavy metal concentrations. Origin Pro 2024 was employed for the multivariate analysis, while Microsoft Excel 2016 was utilized for additional computations.

3. Results

3.1. Physiochemical analysis in Dhaleshwari river water

Temperature is a vital indicator of water quality for the survival of aquatic organisms. Aquatic plants' metabolic rates increase with water temperature, increasing their biochemical oxygen needs and resulting in low DO levels in water (Mumu et al., 2022). The temperature of the river water samples along the 10 sampling sites ranged from 27.09°C to 30.8°C with the mean value of 29.086°C (Table S5). In this study, pH value of the river water samples was neutral to slightly alkaline and ranged from 7.14 to 8.72 with an average value of 7.62 which was exceed to standard value of pH (ECR'23). Changing the pH level can stress the aquatic environment and cause harm to certain fragile aquatic flora and fauna species (Mumu et al., 2022). What is a lake or river's ORP (Oxygen Reduction Potential)? It shows how well it can clean itself or break down waste like impurities and dead animals and plants. There is a lot of oxygen in the water when the ORP number is high. Water is less likely to oxidize when the ORP is negative. The Dhaleshwari river water sample had a maximum ORP value of -200.5 mV and a minimum of -560 mV. The average ORP value was to be -283.36 mV, indicating that the Dhaleshwari river water was antioxidizing in nature. To understand the water environment and determine whether it is good for irrigation and wildlife, monitoring the amount of DO is crucially important. The DO values of the water samples ranged from 0.18 mg/l to 6.4 mg/l. The average value of DO in the recent study of Dhaleshwari river water was 4.5 mg/l, suggesting river water samples were polluted and potentially highly warning for aquatic life. The EC values of water samples ranged from 169 $\mu\text{S}/\text{cm}$ to 9252 $\mu\text{S}/\text{cm}$, with an average value of 1467.7 $\mu\text{S}/\text{cm}$. The maximum TDS value of

water sample was found to be 4149 mg/l, and minimum of the sample was 78 mg/l. The mean TDS value was found to be 673.3 mg/l (Table S5). Salinity and acidity are indicated by electrical conductivity (EC) and pH, respectively, whereas dissolved oxygen (DO) and total dissolved solids (TDS) reflect the organic load present in the water samples.

3.2 Heavy metal pollution assessment

3.2.1 Heavy metal concentration of surface water in Dhaleshwari River

The result of heavy metal (As, Cd, Co, Cr, Cu, Fe, Mn, Ni, Pb, Zn, Se and V) concentrations in the Dhaleshwari River water is shown in Table S6 and Fig. S1. The high Cr content (Fig. 2) in the Dhaleshwari River water may be attributed to an extensive discharge of savor tannery waste, residential sewage, and agricultural runoff. The concentrations of heavy metals in river water play a significant effect in the toxicity of aquatic organisms.

In this present study, the CV values for As, Cd, Co, Cr, Cu, Fe, Mn, Ni, Pb, Zn, Se and V in the surface water samples were 48.49, 23.87, 26.61, 222.98, 100.24, 29.518, 54.24, 96.39, 40.27, 62.34, 78.43 and 63.22% respectively (Table S6). The study's results suggests that Cr, Cu, Mn, Ni, Zn, Se and V contamination levels were mainly influenced by anthropogenic activities throughout the sampling sites.

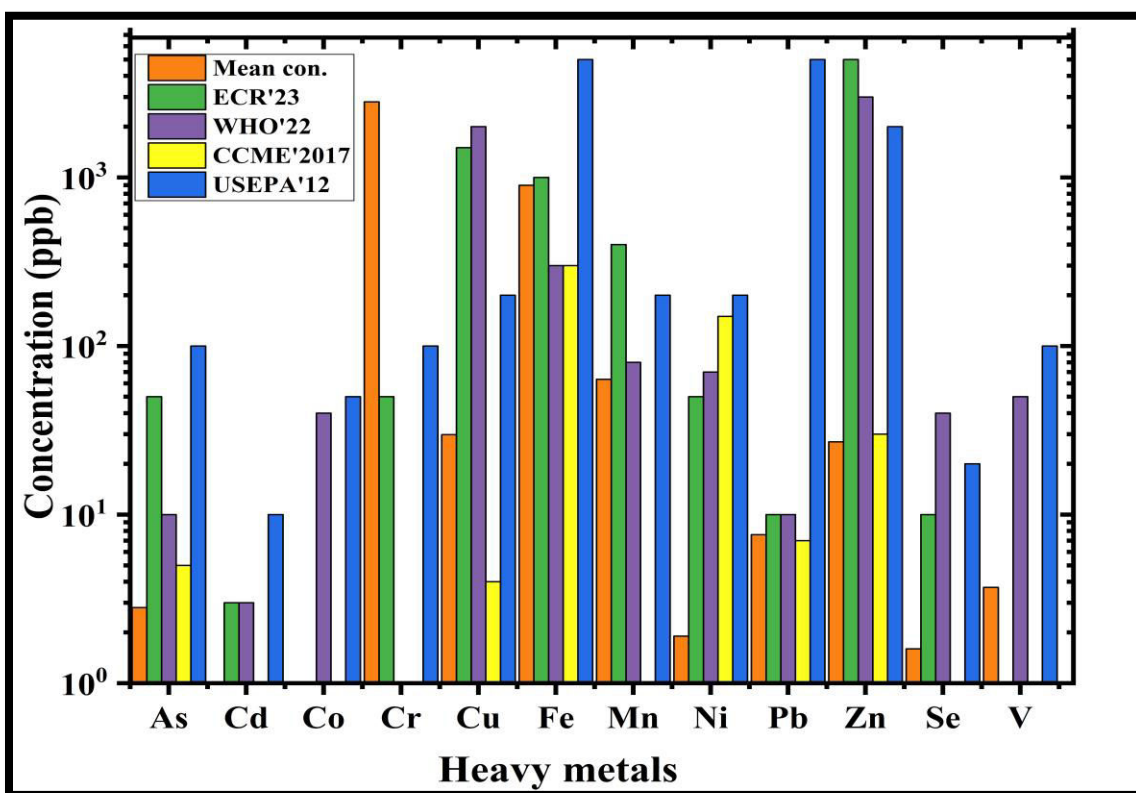


Fig. 2: Average concentration of heavy metals in Dhaleshwari river water

3.2.2 Heavy Metal Toxicity Load (HMTL)

The HMTL index is applied to evaluate the toxicity level of pollutants in water, specifically focusing on the non-carcinogenic risk. Based on the research conducted by Huang et al. (2021), it is recommended that 98.20%, 71.54%, 68.88%, and 7.97% of the As, Cd, Sb, and Mn present in surface water should be eliminated in order to ensure safety, as determined by the total heavy metal toxicity load (HMTL). This index aids in the development of an effective treatment and management strategy (Huang et al., 2021; Kumar et al., 2019). According to the calculated total HMTL, 64.35%, 56.34%, 78.73%, 99.82%, 87.4%, and 86.87% of AS, Cd, Co, Cr, Mn, and Pb in the surface water need to be eliminated from the Dhaleshwari River (Table S7). The elimination of surplus metals from the aquatic environment is necessary in order to effectively mitigate safety and health-related issues. The HMTL index gives the regulatory authority information on the degree of treatment needed to bring the river water's quality down to a point where it is safe to drink.

3.2.3 Single factor pollution Index (Pi) and Nemerow's Pollution Index (P_N)

Fig.S1 illustrates the distribution pattern of heavy metal contamination at different sampling sites. The untreated effluent that is released from the tanneries that are located next to the Dhawleshawri River is the cause of the elevated chromium levels. The average value of P_N was 41.201 and the range was 1.619 to 281.428 (Table S8). The evaluation of Nemerow's pollution index (P_N) suggests that all the water samples were moderately to seriously pollute. These indexes were calculated according to the WHO (2022) drinking water standard.

3.2.4 Metal index (MI)

Metal Index showed that the water quality was poor (71.63), which means that heavy metals are badly affecting the river (Abdullah, 2013). In this study, the average value of the metal index was calculated to be 67.8 (Table 1). According to metal index values, all the sampling sites indicate a threshold warning (MI > 1), along with the sampling sites of S₅, S₆, and S₇, which were observed to be seriously affected (Fig. 3) by metal pollution for drinking purposes. This finding may be associated with the wastewater released from leather industries, dying industries are located in the vicinity of the Dhawleshawri River.

3.2.5 Heavy metal pollution Index (HPI)

The Dhaleshwari River water's average heavy metal pollution index was found to be 136.58 (HPI>100), exceeding a critical index threshold of 100 that indicates unsatisfactory river water quality for irrigation (Fig. 3). The majority of the collected samples represented HPI values below the critical index level, which indicated excellent water quality for irrigation purposes (Table 1). Sampling points S₅, S₆, and S₇ were exceptions; these three sampling sites represented river water quality that was unsuitable for irrigation purposes (Table 1). The high levels of pollution index values may be caused by heavy metals seeping from the Dhaleshwari River's tannery industries. It is crucial to explicitly mention that among the

different heavy metals, Cr was identified as a potential element contributing to the high pollution index value. The average HPI of 2097 greatly exceeds the critical threshold of 100, suggesting that the Diyala River is severely contaminated with heavy metals (Zn, Ni, Cd, Cu, Pb and Cr) (Abdullah, 2013).

3.2.6 Heavy Metal Evaluation Index (HEI)

The average Heavy Metal Evaluation Indexes of the Dhaleshwari River water were calculated to be 28.9684 (Table 1), which suggests river water quality is not suitable for irrigation purposes (According to HEI Categories) (Fig. 3).

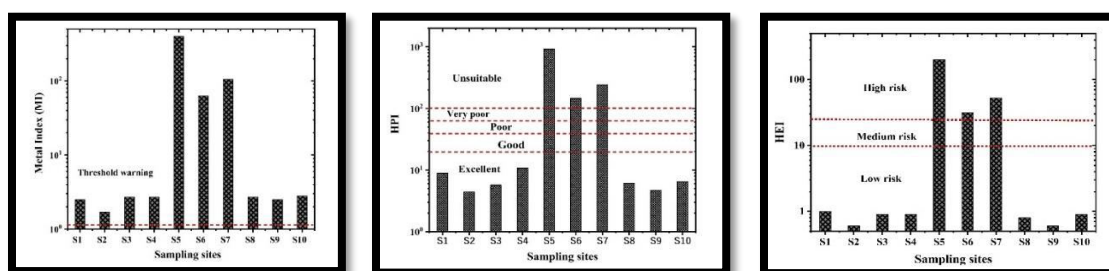


Fig. 3: Metal index (MI), Heavy metal pollution index (HPI), Heavy metal evaluation index (HEI) in different sampling sites of Dhaleshwari River

Table 1: Calculated values of Metal Index (MI), Heavy Metal Pollution Index (HPI) and Heavy Metal Evaluation Index (HEI)

Sampling sites	Water quality for drinking purpose		Water quality for irrigation purpose		
	MI	Status	HPI	HEI	Status
S1	2.5	Threshold warning	8.9	1	Suitable
S2	1.7	Threshold warning	4.4	0.6	Suitable
S3	2.7	Threshold warning	5.7	0.9	Suitable
S4	2.7	Threshold warning	10.8	0.9	Suitable
S5	399.18	Threshold warning	927.3	199.9	Not suitable
S6	63.1	Threshold warning	146.4	31.4	Not suitable
S7	104.6	Threshold warning	244.2	52.6	Not suitable
S8	2.7	Threshold warning	6.1	0.8	Suitable
S9	2.5	Threshold warning	4.7	0.6	Suitable
S10	2.8	Threshold warning	6.5	0.9	Suitable
Average	67.8	Threshold warning	136.6	28.1	Not suitable
Remarks	MI>1	Threshold warning	HPI > 100	HEI > 20	Not suitable

Source: Bangladesh Drinking Water Quality standard (ECR'23); USEPA, 2012 [guideline of water quality criteria for irrigation]; *Bold value indicates high risk of water quality

3.2.7 Degree of contamination (Cd) and Pollution Load Index (PLI)

The evaluation of integrated metal contamination in water was conducted by measuring the level of pollution (Cd). The degree of pollution at most sites showed a very high level of pollution and followed the descending order of $S_5 > S_7 > S_6 > S_4 > S_8 > S_1 > S_{10} > S_3 > S_2 > S_9$ (Fig.6). The degree of pollution (Cd) of specific heavy metals in the studied water has a very high pollution level, where the range of degree of pollution was 2275.02 to 44.91 (Table 2). Among the studied metals, Cd and Cr showed very high contamination at some sites, whereas As, Ni, and Zn posed a very low contamination factor at most of the sampling sites.

The PLI values ranged from 1.09 to 3.18, and the mean PLI value was 1.77 (Table 2), confirming that the water of the studied river was moderately polluted ($PLI > 1$). Higher PLI values were observed at sampling sites S6 and S7, which might be due to the effects of tannery effluents (Fig. 4).

3.2.8 Ecological Risk Index (ERI)

Hakanson (1980) developed a methodology for evaluating ecological risks in the context of reducing water pollution (Hakanson, 1980). The studied 12 metals (Mg, V, Cr, Mn, Fe, Co, Ni, Zn, As, Cd, Sb, and Ba) pose a high ecological risk, as shown by the ecological risk index (RI) ($RI > 600$). According to Ubuoh et al., 2023, the study found that the contamination and ecological risk levels were relatively low to moderate. This can be mainly attributable to the self-purification properties of a flowing river or stream, which effectively reduces pollution load and associated risks (Ubuoh et al., 2023). According to the CCME standard, the calculated Ecological Risk Index of the toxic metals for Dhaleshawri river water ranged from 1109.3 to 5444.9 and the mean ERI was found to be 1109.3, which indicates higher Ecological Risk ($ERI > 600$) (Table 2). The order of significance of the potential ecological risk factor of heavy metals in the surface water of the Dhaleshawari river represents $Cd > Cr (S_5, S_6, S_7) > Cu (S_2)$ (Fig. 4).

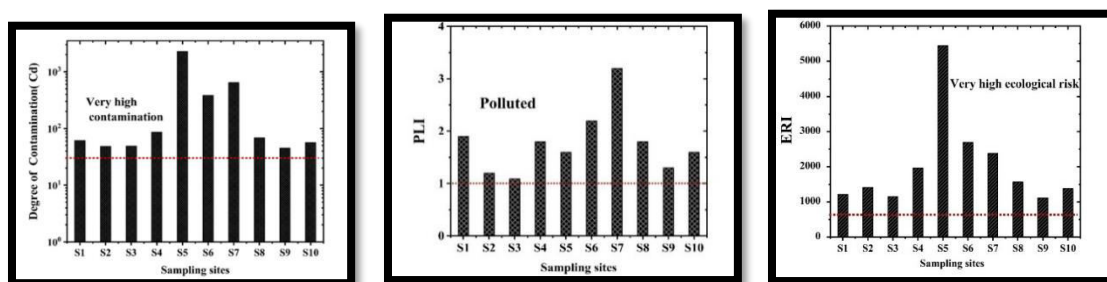


Fig. 4: Degree of contamination (Cd), Pollution load index (PLI) and Ecological risk index (ERI) in different sampling sites of Dhaleshwari River

Table 2: Calculated values of degree of contamination (C_d), Pollution Load Index (PLI) and Ecological Risk Index(ERI)

Samplin g sites	C_d	Contaminatio n level	PLI	water quality for aquatic life	ERI	Ecological risk level
S₁	61.3	very high	1.9	polluted	1214.5	Very high risk
S₂	48.3	very high	1.2	polluted	1412.7	Very high risk
S₃	48.8	very high	1.09	polluted	1149.3	Very high risk
S₄	85.6	very high	1.8	polluted	1968.25	Very high risk
S₅	2275.01	very high	1.6	polluted	5444.9	Very high risk
S₆	383.2	very high	2.2	polluted	2693.8	Very high risk
S₇	644.03	very high	3.2	polluted	2377.9	Very high risk
S₈	68.7	very high	1.8	polluted	1565.3	Very high risk
S₉	44.9	very high	1.3	polluted	1109.3	Very high risk
S₁₀	56.3	very high	1.6	polluted	1382.8	Very high risk
Average	371.6	very high	1.8	polluted	2228.3	Very high risk
Remarks	HC: $C_d > 32$	very high contamination	PLI > 1	polluted	ERI > 600	Very high ecological risk in aquatic environme nt
Source: Canadian Water Quality Guidelines for the protection of aquatic life [CCME, 2017]						

3.2.9 Human Health Risk Assessment

The quality of river water was evaluated using a health risk assessment due to its prolonged consumption. Health risk assessment revealed that children had a higher vulnerability than adults to the non-carcinogenic risk associated with dissolved metals (Mg, V, Cr, Mn, Fe, Co, Ni, Zn, As, Cd, Sb, and Ba) (Huang et al., 2021).

3.2.9.1 Hazard Quotient (HQ) for oral intake

The mean Hazard Quotient values for adults and Children were represented as Table S9. Each of these values is below the threshold value of 1 ($HQ < 1$). The mean HQ values of Cr ranged from 66.0510 to 62.371, indicating a statistically significant increase over the established threshold ($HQ > 1$), which are warning signs of a significant health risk in Dhaleshwari river water (Fig.9).

3.2.9.2 Hazard Quotient (HQ) for dermal intake

The mean HQ values of Cr, As, Cd, Mn, Pb, and V were found to be above 1 ($HQ > 1$) for both adults and children, indicating that these elements have warning signs of a significant health risk in Dhaleshwari river water (Table S10 & Fig. 5). Chromium (Cr), cadmium (Cd), lead (Pb) are commonly present in textile dyeing and tannery effluents (Juel et al., 2016; Velusamy et al., 2021). The mean HQ values for Co, Cu, Fe, Zn and Ni were less than 1 ($HQ < 1$), Indicating that these elements present minimal or negligible risk.

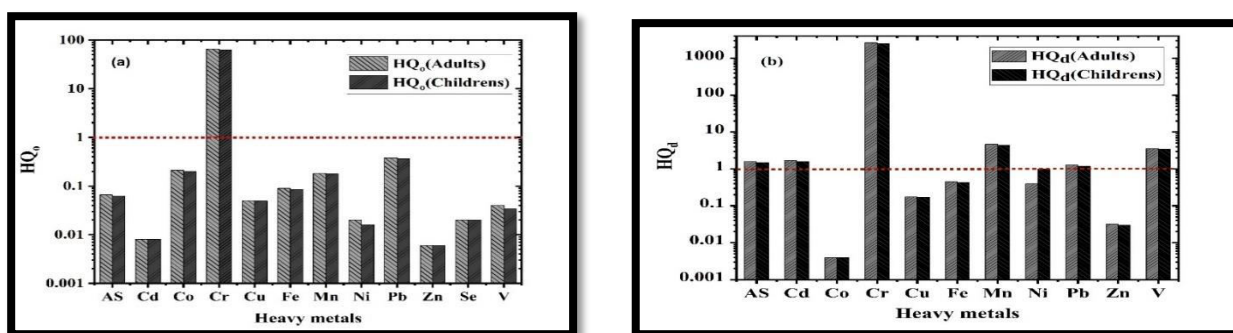


Fig. 5: Non carcinogenic health risk in different sampling sites of water samples for oral intake (a) and dermal intake (b)

3.3 Pollution sources identification

3.3.1 Pearson's correlation analysis

A Pearson correlation study was conducted to examine the relationship between metals and indices (Cd, PLI, HPI, and MI). An analysis was conducted to figure out the correlation between metals and their impact on indices (Table S11). The analysis's results showed that there was a significant correlation between the following pairs at the significance level of $p < 0.05$: As and Co; Cd and Pb; Co and Zn; Cr and Mn, Pb, V; Mn and Pb, Zn, V; Ni and V. According to the result of analysis, significant correlation carried out between metals and indices as following pairs: Cr and Cd (degree of contamination), HPI, MI; Cu and PLI; Mn

and HPI, MI; Zn and PLI; V and HPI, MI. From the analysis of findings, Cr, Cu, Mn, Zn and V demonstrate significant correlations with all the indices, indicating that these metals are major contributory pollution sources (Table S10). It was observed that there was a strongly significant correlation between indices: Cd (degree of contamination) and PLI (pollution load index), HPI (heavy metal pollution index), and MI (metal index). This result shows that both indices are heavily influenced by both the same and different metals. Some negative relationships have been observed Pb with V, Cd, HPI and MI; indicating the sources of the parameters may be both natural and anthropogenic.

3.3.2 Principal Component Analysis (PCA)

Researchers have accepted principal component analysis (PCA) as a valuable tool for source identification. In the principal component analysis (PCA) of heavy metals in the Dhaleshwari River, PC-1 explained 38.86% of the variation in water, while PC-2 explained 23.76% (Fig. S2). The fig.S2 illustrates the bio-plot of principal component analysis (PCA). The results indicate that the water samples (S3- Akh knitting and Dying limited; BSCIC Tannery industrial state represent S5, S6 and S7) demonstrate a positive correlation with principal component 1 (PC1), suggesting a significant influence from the majority of heavy metals. The PCA analysis showed that As, Co, Fe, Pb, Zn, Ni, Mn and Cr all had significant positive loadings. This indicates that both natural and human activities primarily influenced these elements. Cr and V made the most significant contributions in PC1, primarily due to anthropogenic activities like the use of chromium salt for tanning purposes. The effluent from tanneries released in close proximity to the Dhaleshwari River is the primary source of chromium contamination in this study area under evaluation. The second component (PC2) represented 23.76% of the variance, mostly due to the significant loadings of Cd and Se. The source of cadmium comes mainly from dying activities in the textile industry.

4. Discussion

The Savar tannery industrial region, which emits a lot of untreated effluent, is mostly to blame for the extreme pollution of the Dhaleshwari River, which lies near Dhaka. Various indices were used, including PER, Igeo, EF, and TUs to evaluate ecological hazards and analyze sediment concentrations of Pb, Cd, Cr, Ni, and Fe. Heavy metal discharge from tanneries, dyeing units, and other industries into the Dhaleshwari River poses serious health concerns in Bangladesh due to bioaccumulation through fish consumption. Concentrations of Cr, Pb, and Zn were found to be approximately 300, 20, and 10 times higher, respectively, than the FAO/WHO guideline limits, indicating significant potential risks to human health (Wahiduzzaman et al., 2022). Because of its position and biological roles, the Dhaleshwari River was evaluated for heavy metal pollution, contamination levels, and sediment deposit patterns. The majority of sites showed contamination by all tested

heavy metals, according to the pollution load index (PLI), whereas the geo-accumulation index (Igeo) showed low to severe contamination at most sites (Al Mamun et al., 2021). To assess the impact of tannery effluents on the water quality of the Dhaleshwari River near Savar, Dhaka, physicochemical characteristics such as pH, EC, DO, TDS, Cr, Pb, and Cd were examined in order to ascertain the river's present pollution level. According to the study's findings, the Dhaleshwari River exhibits signs of tannery effluent pollution, especially in the areas of heavy metals and microbiological contamination, even though some physicochemical characteristics are within acceptable bounds (M. M. Islam et al., 2025). In the Dhaleshwari River in Bangladesh, atomic absorption spectrophotometry was used to assess the temporal and geographical distribution of heavy metals in the water, sediment, fish, and mussels. Mussels had much higher quantities of all the heavy metals examined than fish, indicating a faster rate of bioaccumulation in mollusks (M. K. Ahmed et al., 2009). Dhaleshwari River's present water quality condition and possible sources of pollution were assessed using physicochemical characteristics, multivariate statistical analysis, and the water quality index (WQI) approach. The primary sources of pollution were found to be municipal wastewater and direct wastewater discharge from nearby enterprises, especially tanneries, according to the results of the principal components analysis used for source appointment. As a result of development and human activity, the Dhaleshwari River's water quality is declining. The results emphasize the pressing need for actions to reduce the sources of pollution and enhance the general well-being of the river ecosystem (Ali et al., 2024).

Global environmental issues include heavy metals, particularly in emerging nations like Bangladesh, as a result of pollution in their river systems. Previous studies on the Dhaleshwari River have documented high levels of heavy metals and their accumulation in aquatic life (M. A. S. Islam et al., 2023; Mohanta et al., 2019). While these studies have effectively used traditional indices like the ecological risk index (ERI) and geo-accumulation index (Igeo) to assess pollution levels, they often focus on quantifying the degree of contamination without providing a clear, actionable metric for remediation. Serious ecological and environmental hazards were indicated by the results, which showed considerable heavy metal enrichment (M. A. S. Islam et al., 2023). Residential, agricultural, and industrial sources generate various non-biodegradable contaminants that accumulate in water, sediment, and the food chain, posing long-term risks to human health and ecosystems (Wahiduzzaman et al., n.d.). Hexavalent Chromium from tannery effluents causes severe harm to aquatic organisms, including DNA damage and reproductive disruptions in fish, while Cadmium bioaccumulation affects plankton and benthic species, and Lead impairs fish behavior and neurological function (H. Rahman et al., 2020; Suchana et al., 2021; Whitehead et al., 2021). We also expanded the assessment of human exposure pathways, noting that communities are affected through the consumption of contaminated

fish, use of polluted river water for daily activities, and occupational exposure in the tannery and textile industries. These exposures are linked to various health issues, including skin disorders from Chromium, kidney and bone problems from Cadmium, and cognitive and cardiovascular effects from Lead (M. K. Ahmed et al., 2009; Lipy et al., 2021; Mohanta et al., 2019).

Heavy metal concentrations (Cr, Cd, Cu, Pb, Ni, and Zn) were measured in order to evaluate the contamination load in the Dhaleswari river water and any potential health risks to humans. Pb concentrations at the main disposal point of the Savar tannery area exceeded the standard value of effluents for inland surface water, and chromium concentrations in the water samples taken from the Dhaleswari River exceeded the maximum allowable concentration (MAC) at the Savar study area. These changes have an impact on the river water environment and thereby reduce ecological balance (Chamon et al., 2023). Savar's tanneries, dyeing plants, and other human-caused sources of heavy metal pollution have frequently polluted the Dhaleswari River, which is an essential waterway for Dhaka. The main source of chromium pollution is the Savar tannery industry since hexavalent chromium is an essential ingredient for the tanning of leather (Wahiduzzaman et al., n.d.). A significant portion of this chromium is discharged into the river as part of the industrial effluent (M. A. S. Islam et al., 2023). This study clarifies that tannery operations are the major source of chromium, as it is a key chemical used in the tanning process. Similarly, we have linked the presence of cadmium and lead to other industrial effluents from battery and pigment businesses in the area. Table 3 provides a more explicit connection between the types of industries and the specific heavy metals detected. Our analysis revealed that the Dhaleswari River is significantly contaminated with several heavy metals. The concentrations of Cr, Pb, and Cd, in particular, consistently exceeded the permissible limits for drinking water and aquatic life as defined by the WHO and FAO (Rehnuma et al., 2024). The concentrations of these metals were found to be higher near the industrial discharge points, especially during the dry season, when the river's flow is lower and pollutants are less diluted (Wahiduzzaman et al., n.d.). The elevated levels of heavy metals can be directly linked to specific anthropogenic activities in the region. Other industries, such as those involved in battery manufacturing and pigment production, contribute to the high concentrations of lead and cadmium found in the river (Rehnuma et al., 2024).

Table 3: Comparison of the heavy metals source

Metal	Primary Source	Activity Stage	Key References
Cr	Basic chromium sulfate	Tanning	(Hossain et al., 2021; M. A. T. M. Rahman et al., 2020)
Cd	Cd-based pigments, electroplating	Dyeing, finishing	(A. S. S. Ahmed et al., 2021; Proshad et al., 2021)

Metal	Primary Source	Activity Stage	Key References
Pb	Pb chromate pigments, PVC stabilizers, and lubricants	Finishing, machinery	(Bodrud-Doza et al., 2019; Chowdhury et al., 2015)

The use of a multi-index approach provided a comprehensive view of the river's pollution status. The HPI and HEI values indicated a severe level of heavy metal pollution, which is consistent with the findings of other studies on peripheral rivers of Dhaka (Mohanta et al., 2019). The ERI further confirmed that the contamination poses a significant ecological risk to aquatic organisms. Our application of the HMTL method, however, offered a unique and practical perspective. While the ERI and HI are useful for a general assessment of risk, they do not provide a clear path for remediation. In contrast, the HMTL results provided a quantitative estimate of the specific percentage of heavy metals that would need to be removed from the water to meet safety standards. For instance, our data shows that a 99.8% reduction in chromium levels and a 86.9% reduction in lead levels are necessary to make the water safe for human health, providing policymakers with a tangible target for pollution control. The comparison of pollution indices in this study are shown in Table 4. This comparison evaluates their purpose, strengths, limitations, and specific performance in assessing the Dhaleshwari River.

The observed heavy metal contamination poses severe risks to both the ecosystem and the local population. Studies have shown that heavy metals like Cr and Pb bioaccumulate in fish tissues and local vegetables irrigated with river water (Wahiduzzaman et al., n.d.). The consumption of these contaminated fish and vegetables can lead to a range of health issues, including kidney damage, neurological disorders, and an increased risk of cancer (Rehnuma et al., 2024).

Table 4: Critical comparison of the pollution indices in this study

Index	Primary Purpose	Strengths	Limitations	Key Findings
HMTL (Heavy Metal Toxicity Load)	Quantifies % removal needed to meet safe limits	Actionable for treatment design; prioritizes metals	Requires accurate Hazard Intensity Score (HIS) data; less used in literature	Cr (99.8 %), Mn (87.4 %), Pb (86.9 %) require highest removal
HPI (Heavy Metal Pollution Index)	Aggregates multiple metals into a single water quality score	Simple, widely used in Bangladesh	Does not indicate treatment needs; equally weights all metals	HPI > 100 at all stations indicates water unsuitable for drinking
HEI (Heavy Metal)	Irrigation water suitability	Quick assessment; sensitive to	Ignores ecological effects	HEI > 28 at downstream sites:

Index	Primary Purpose	Strengths	Limitations	Key Findings
Evaluation Index)		metals with high standards		unsuitable for irrigation
ERI (Ecological Risk Index)	Ecological risk from metals	Considers toxic response factors; highlights high-risk metals	Needs accurate background values; sediment-focused in some studies	ERI > 600: very high risk, mainly from Cr and Cd
PLI (Pollution Load Index)	Indicates overall contamination status	Easy to interpret	Does not identify specific pollutant sources or risks	PLI > 1 at all sites: high contamination

We argue that a multi-index approach is necessary for a holistic assessment. The traditional indices (HPI, HEI, ERI) were used to provide a comparative context and to validate our findings against previous studies. The HMTL was then used to provide a unique, action-oriented perspective on the contamination level. The combined use of these indices offers a more comprehensive and informative assessment of the Dhaleshwari River's pollution status (Table 5).

Table 5: Comparative utility of pollution indices in this study

Index	Decision-Making Purpose	Relevance to Dhaleshwari River
HMTL	Designing remediation/treatment strategies	Evaluates the exact removal percentage needed for key metals such as Cr, Pb, and Mn.
HPI	Screening human health risk	Confirms that water quality exceeds safe drinking standards.
HEI	Assessing irrigation water quality	Highlights potential for heavy metal uptake by crops.
ERI	Evaluating ecological threats	Identifies Cr and Cd as key ecological hazards
PLI	General contamination diagnosis	Provides quick spatial overall pollution load.

HMTL bridges this gap by producing removal percentage targets based on Hazard Intensity Scores (HIS) and measured concentrations outputs directly applicable for treatment design and policy-making (Saha & Paul, 2018; Huang et al., 2021). Applying HMTL, our findings show Cr (99.8 %), Mn (87.4 %), Pb (86.9 %) removal is essential—actionable data that no prior Dhaleshwari study has reported. While HMTL has been applied in China (Huang et

al., 2021) and India (Kumar et al., 2019), its use in South Asia for tannery-polluted rivers is absent. Our study adapts and validates HMTL in a developing country context with extreme point-source pollution, making it relevant for both local management and international comparative research. The Heavy Metal Toxicity Load (HMTL) approach was successfully used for the first time in this study to assess the pollution condition of the Dhaleshwari River. Our data reveal that the river is significantly contaminated with chromium, lead, and cadmium, mostly due to industrial discharges. The HMTL technique, when combined with established indices, provides a comprehensive and actionable evaluation, resulting in a clear quantifiable objective for pollution reduction. This study emphasizes the critical need for a properly operational and enforced pollution control system in the industries near the Dhaleshwari River. The findings serve as a vital reference for future environmental monitoring and repair initiatives aimed at protecting the river's ecological health and the well-being of the populations that depend on it.

5. Conclusions

According to the study's findings, surface water that contains heavy metals is harmful to both the environment and human health. Most metals come from anthropogenic activities, including high levels of Tannery effluent and other industrial wastewater. In this study, the MI result was 58.45 ($MI > 1$), indicating that the river water is unsafe to drink. Based on the average concentration of the heavy metals, the total HPI was determined to be 136.58, exceeding the crucial threshold pollution index value of 100, and the mean result of HEI was also calculated to be 28.9 ($HEI > 20$), indicating that the selected water quality is not very suitable for irrigation purposes. Total heavy metal toxicity load (HMTL) values indicate a higher toxicity load of metals in surface water. The metals As, Cd, Co, Cr, Mn, and Pb in the Dhaleshwari River have a higher heavy metal toxicity load (HMTL) than the permissible limit. The degree of contamination at most of the sites showed a very high level of pollution, where the pollution degree ranged from 2275 to 44.91. The overall PLI was 1.77, confirming that the water of the studied river is moderately polluted ($PLI > 1$), and higher PLI were observed at sampling sites S6 and S7, which might be due to the effects of tannery effluents. The mean ERI was found to be 1109.3, indicating a high ecological risk from the studied metals ($ERI > 600$). We are all concerned about the Buriganga River because of its deterioration. As we know, the Buriganga River is also called the Dead River. To save this river, the largest tannery estate relocated to Savar, which is situated near the Dhaleshwari River. From above, the findings represent the present condition of the Dhaleshwari River, and it is clear to us that tannery effluent discharges into river water without proper use of CETP. Imagine if we were able to construct infrastructure without enough planning, and later, when we became aware that it was negatively impacting our natural environment, we could dismantle and relocate it. The impact on natural resources is permanent, even if we

can move infrastructure around as we like. We must focus on an economic perspective as well as be concerned about the environment and social impact.

Declaration

The authors of the text attest that they are not associated with or involved with any organization or entity that has a financial interest in the topics or materials included in this research.

Data availability

Data are available on the supplementary file.

Acknowledgments

We express our sincere gratitude to each and every co-author for their outstanding assistance in completing our study.

References:

1. Abdel-Satar, A.M., Ali, M.H., Goher, M.E., 2017. Indices of water quality and metal pollution of Nile River, Egypt. *Egypt. J. Aquat. Res.* 43.
2. Abdullah, E.J., 2013. Evaluation of surface water quality indices for heavy metals of Diyala River-Iraq. *J. Nat. Sci. Res.* 3.
3. Ahmed, A.S.S., Hossain, M.B., Babu, S.M.O.F., Rahman, M.M., Sarker, M.S.I., 2021. Human health risk assessment of heavy metals in water from the subtropical river, Gomti, Bangladesh. *Environ. Nanotechnology, Monit. Manag.* 15, 100416.
4. Ahmed, M.K., Ahamed, S., Rahman, S., Haque, M.R., Islam, M.M., 2009. Heavy metals concentration in water, sediments and their bioaccumulations in some freshwater fishes and mussel in Dhaleshwari River, Bangladesh. *Terr Aquat Env. Toxicol* 3, 33–41.
5. Al-Saleh, I., Abduljabbar, M., 2017. Heavy metals (lead, cadmium, methylmercury, arsenic) in commonly imported rice grains (*Oryza sativa*) sold in Saudi Arabia and their potential health risk. *Int. J. Hyg. Environ. Health* 220.
6. Al Mamun, A., Sarker, P., Rahaman, M.S., Kabir, M.M., Maruo, M., 2021. Evaluation of contamination and accumulation of heavy metals in the Dhaleswari river sediments, Bangladesh. *Int. J. Environ.* 10, 1–19.
7. Ali, M.M., Ali, M.L., Islam, M.S., Rahman, M.Z., 2018. Assessment of toxic metals in water and sediment of Pasur River in Bangladesh. *Water Sci. Technol.* 77, 1418–1430.
8. Ali, M.M., Rahman, S., Islam, M.S., Rakib, M.R.J., Hossen, S., Rahman, M.Z., Kormoker, T., Idris, A.M., Phoungthong, K., 2022. Distribution of heavy metals in water and sediment of an urban river in a developing country: A probabilistic risk assessment. *Int. J. Sediment Res.* 37.

9. Ali, M.S., Begum, S., Rabbi, F.M., Sumaia, Hasan, M.K., Rahman, M.A., Rahman, M.M., Rahaman, M.H., 2024. Multivariate analysis of water quality in the Dhaleshwari River, Bangladesh: identifying pollution sources and environmental implications. *Water Pract. Technol.* 19, 4128–4147.
10. Association, A.P.H., 1926. Standard methods for the examination of water and wastewater. American Public Health Association.
11. ATSDR, 2022. Agency for Toxic Substances and Disease Registry. Toxicological Profile for Copper (Draft for Public Comment). Atlanta, GA: U.S. Department of Health and Human Services. Public Heal. Serv.
12. Badeenezhad, A., Soleimani, H., Shahsavani, S., Parseh, I., Mohammadpour, A., Azadbakht, O., Javanmardi, P., Faraji, H., Babakrpur Nalosi, K., 2023. Comprehensive health risk analysis of heavy metal pollution using water quality indices and Monte Carlo simulation in R software. *Sci. Rep.* 13, 15817.
13. Bodrud-Doza, M., Islam, S.M.D.U., Hasan, M.T., Alam, F., Haque, M.M., Rakib, M.A., Asad, M.A., Rahman, M.A., 2019. Groundwater pollution by trace metals and human health risk assessment in central west part of Bangladesh. *Groundw. Sustain. Dev.* 9.
14. Caeiro, S., Costa, M.H., Ramos, T.B., Fernandes, F., Silveira, N., Coimbra, A., Medeiros, G., Painho, M., 2005. Assessing heavy metal contamination in Sado Estuary sediment: an index analysis approach. *Ecol. Indic.* 5, 151–169.
15. Chamon, A., Romana, S., Zubaer, M., Prian, W., Hossain, M., Mondol, M., 2023. Dhaleshwari River Water Quality Due to Disposal of Tannery Wastes at Savar, Dhaka, Bangladesh.
16. Chowdhury, M., Mostafa, M.G., Biswas, T.K., Mandal, A., Saha, A.K., 2015. Characterization of the effluents from leather processing industries. *Environ. Process.* 2, 173–187.
17. Dey, M., Akter, A., Islam, S., Dey, S.C., Choudhury, T.R., Fatema, K.J., Begum, B.A., 2021. Assessment of contamination level, pollution risk and source apportionment of heavy metals in the Halda River water, Bangladesh. *Heliyon* 7.
18. Edet, A.E., Offiong, O.E., 2002. Evaluation of water quality pollution indices for heavy metal contamination monitoring. A study case from Akpabuyo-Odukpani area, Lower Cross River Basin (southeastern Nigeria). *GeoJournal* 57.
19. Edokpayi, J.N., Odiyo, J.O., Durowoju, O.S., 2017. Impact of wastewater on surface water quality in developing countries: a case study of South Africa. *Water Qual.* 10, 10–5772.
20. Hakanson, L., 1980. An ecological risk index for aquatic pollution control: a sedimentological approach. *Water Res.* 14.
21. Haque, M.M., Niloy, N.M., Nayna, O.K., Fatema, K.J., Quraishi, S.B., Park, J.H., Kim,

- K.W., Tareq, S.M., 2020. Variability of water quality and metal pollution index in the Ganges River, Bangladesh. *Environ. Sci. Pollut. Res.* 27.
22. Haque, M.R., Ali, M.M., Ahmed, W., Rahman, M.M., 2022. Assessment of metal(loid)s pollution in water and sediment from an urban river in Bangladesh: An ecological and health risk appraisals. *Case Stud. Chem. Environ. Eng.* 6.
23. Hasan, M.M., Ahmed, M.S., Adnan, R., 2020. Assessment of physico-chemical characteristics of river water emphasizing tannery industrial park: a case study of Dhaleshwari River, Bangladesh. *Environ. Monit. Assess.* 192.
24. Hossain, M.B., Semme, S.A., Ahmed, A.S.S., Hossain, M.K., Porag, G.S., Parvin, A., Shanta, T.B., Senapathi, V., Sekar, S., 2021. Contamination levels and ecological risk of heavy metals in sediments from the tidal river Halda, Bangladesh. *Arab. J. Geosci.* 14.
25. Hossain, S.M.S., Haque, M.E., Pramanik, M.A.H., Uddin, M.J., Al Harun, M.A.Y., 2020. Assessing the groundwater quality and health risk: A case study on Setabganj sugar mills limited, Dinajpur, Bangladesh. *Water Sci.* 34, 110–123.
26. Hossen, M.A., Mostafa, M.G., 2023. Assessment of heavy metal pollution in surface water of Bangladesh. *Environ. Challenges* 13.
27. Huang, Z., Zheng, S., Liu, Y., Zhao, X., Qiao, X., Liu, C., Zheng, B., Yin, D., 2021. Distribution, toxicity load, and risk assessment of dissolved metal in surface and overlying water at the Xiangjiang River in southern China. *Sci. Rep.* 11.
28. Islam, M.A.S., Hossain, M.E., Majed, N., 2021. Assessment of Physicochemical Properties and Comparative Pollution Status of the Dhaleshwari River in Bangladesh. *Earth (Switzerland)* 2.
29. Islam, M.A.S., Hossain, M.E., Nahar, K., Majed, N., 2023. Assessment of environmental Hazard and heavy metal contamination in Dhaleshwari River sediment: a toxicity based study on pollution. *Pollution* 9, 67–83.
30. Islam, M.M., Rahman, T., Urmi, A.A.Z., Mamun, M.I.R., Shoeb, M., 2025. Impact of the tannery industrial zone on the physicochemical and microbiological quality of the Dhaleshwari river water, Bangladesh. *J. Bangladesh Acad. Sci.* 49, 45–55.
31. Islam, M.S., Kabir, M.H., Ali, M.M., Islam, M.T., Niger, A., Ismail, Z., Ahmed, S., Ibrahim, K.A., Idris, A.M., 2023. Assessment of ecological risk for heavy metals in surface sediment of an urban river in a developing country. *Int. J. Sediment Res.* 38.
32. Jaishankar, M., Tseten, T., Anbalagan, N., Mathew, B.B., Beeregowda, K.N., 2014. Toxicity, mechanism and health effects of some heavy metals. *Interdiscip Toxicol* 7: 60–72.
33. Jiang, H.H., Cai, L.M., Wen, H.H., Hu, G.C., Chen, L.G., Luo, J., 2020. An integrated approach to quantifying ecological and human health risks from different sources of soil heavy metals. *Sci. Total Environ.* 701.

34. Juel, M.A.I., Chowdhury, Z.U.M., Ahmed, T., 2016. Heavy metal speciation and toxicity characteristics of tannery sludge, in: AIP Conference Proceedings. AIP Publishing.
35. Kubra, K., Mondol, A.H., Ali, M.M., Palash, M.A.U., Islam, M.S., Ahmed, A.S.S., Masuda, M.A., Islam, A.R.M.T., Bhuyan, M.S., Rahman, M.Z., 2022. Pollution level of trace metals (As, Pb, Cr and Cd) in the sediment of Rupsha River, Bangladesh: assessment of ecological and human health risks. *Front. Environ. Sci.* 10, 778544.
36. Kumar, V., Parihar, R.D., Sharma, A., Bakshi, P., Singh Sidhu, G.P., Bali, A.S., Karaouzas, I., Bhardwaj, R., Thukral, A.K., Gyasi-Agyei, Y., Rodrigo-Comino, J., 2019. Global evaluation of heavy metal content in surface water bodies: A meta-analysis using heavy metal pollution indices and multivariate statistical analyses. *Chemosphere*.
37. Kumar, V., Sharma, A., Kumar, R., Bhardwaj, R., Kumar Thukral, A., Rodrigo-Comino, J., 2020. Assessment of heavy-metal pollution in three different Indian water bodies by combination of multivariate analysis and water pollution indices. *Hum. Ecol. risk Assess. an Int. J.* 26, 1–16.
38. Kumar, V., Sharma, A., Minakshi, Bhardwaj, R., Thukral, A.K., 2018. Temporal distribution, source apportionment, and pollution assessment of metals in the sediments of Beas river, India. *Hum. Ecol. Risk Assess. An Int. J.* 24, 2162–2181.
39. Mohanta, L.C., Niloy, M.N.H., Chowdhury, G.W., Islam, D., Lipy, E.P., 2019. Heavy metals in water, sediment and three fish species of Dhaleshwari river, Savar. *Bangladesh J. Zool.* 47, 263–272.
40. Monira, U., Sattar, G.S., Mostafa, M.G., 2023. Characterization and Removal Efficiency of Central Effluent Treatment Plant (CETP). *J. Sustain. Environ. Manag.* 2, 42–50.
41. Mumu, N.J., Jahangir, M.M.R., Mahjabin, F., Al, M.A., Asif, M.S., Islam, M.R., 2022. Tannery industry impacts on hydrogeochemistry and heavy metal contents of two major rivers in Dhaka.
42. Prasanna, M. V., Praveena, S.M., Chidambaram, S., Nagarajan, R., Elayaraja, A., 2012. Evaluation of water quality pollution indices for heavy metal contamination monitoring: A case study from Curtin Lake, Miri City, East Malaysia. *Environ. Earth Sci.* 67.
43. Proshad, R., Islam, S., Tusher, T.R., Zhang, D., Khadka, S., Gao, J., Kundu, S., 2021. Appraisal of heavy metal toxicity in surface water with human health risk by a novel approach: a study on an urban river in vicinity to industrial areas of Bangladesh. *Toxin Rev.* 40.
44. Qu, L., Huang, H., Xia, F., Liu, Y., Dahlgren, R.A., Zhang, M., Mei, K., 2018. Risk analysis of heavy metal concentration in surface waters across the rural-urban

- interface of the Wen-Rui Tang River, China. *Environ. Pollut.* 237, 639–649.
45. Rahman, M.A.T.M., Paul, M., Bhoumik, N., Hassan, M., Alam, M.K., Aktar, Z., 2020. Heavy metal pollution assessment in the groundwater of the Meghna Ghat industrial area, Bangladesh, by using water pollution indices approach. *Appl. water Sci.* 10, 1–15.
46. Rakib, R.J., Hossain, M.B., Jolly, Y.N., Akther, S., Islam, S., 2022. EDXRF Detection of Trace Elements in Salt Marsh Sediment of Bangladesh and Probabilistic Ecological Risk Assessment. *Soil Sediment Contam.* 31.
47. Rampley, C.P.N., Whitehead, P.G., Softley, L., Hossain, M.A., Jin, L., David, J., Shawal, S., Das, P., Thompson, I.P., Huang, W.E., Peters, R., Holdship, P., Hope, R., Alabaster, G., 2020. River toxicity assessment using molecular biosensors: Heavy metal contamination in the Turag-Balu-Buriganga river systems, Dhaka, Bangladesh. *Sci. Total Environ.* 703.
48. Registry, A. for T.S. and D., 2017. Substance priority list.
49. Rehnuma, M., Jui, J.F., Hasna, J., Habiba, U., Haque, A., 2024. Assessment of Water Quality and Heavy Metal Contamination in River Water and Fish Species from the Bangshi River, Tangail, Bangladesh. *J. Agrofor. Environ.* 17, 205–212.
50. Rice, E.W., Bridgewater, L., Association, A.P.H., 2012. Standard methods for the examination of water and wastewater. American public health association Washington, DC.
51. Safiur Rahman, M., Shafiuddin Ahmed, A.S., Rahman, Md Moshiur, Omar Faruque Babu, S.M., Sultana, S., Sarker, S.I., Awual, R., Rahman, Mohammad Majibur, Rahman, M., 2021. Temporal assessment of heavy metal concentration and surface water quality representing the public health evaluation from the Meghna River estuary, Bangladesh. *Appl. Water Sci.* 11.
52. Saha, P., Paul, B., 2019. Assessment of heavy metal toxicity related with human health risk in the surface water of an industrialized area by a novel technique. *Hum. Ecol. risk Assess. an Int. J.*
53. Sahoo, M.M., Swain, J.B., 2020. Modified heavy metal Pollution index (m-HPI) for surface water Quality in river basins, India. *Environ. Sci. Pollut. Res.* 27.
54. Taiwo, A.M., Michael, J.O., Gbadebo, A.M., Oladoyinbo, F.O., 2020. Pollution and health risk assessment of road dust from Osogbo metropolis, Osun state, Southwestern Nigeria. *Hum. Ecol. Risk Assess.* 26.
55. Tyagi, S., Sarma, K., 2021. Expounding major ions chemistry of groundwater with significant controlling factors in a suburban district of Uttar Pradesh, India. *J. Earth Syst. Sci.* 130, 169.
56. Ubuoh, E.A., Nwogu, F.U., Ofoegbu, C.C., Chikezie, P.C., 2023. Environmental pollution loads on surface water chemistry and potentially ecological risks of inland

- aquatic ecosystem in South-Eastern State, Nigeria. *Environ. Syst. Res.* 12, 22.
57. Uddin, M., Alam, F. Bin, 2023. Health risk assessment of the heavy metals at wastewater discharge points of textile industries in Tongi, Shitalakkhya, and Dhaleshwari, Bangladesh. *J. Water Health* 21.
58. Uddin, M.J., Jeong, Y.K., 2021. Urban river pollution in Bangladesh during last 40 years: potential public health and ecological risk, present policy, and future prospects toward smart water management. *Heliyon*.
59. USEPA, 2012. Guidelines for Water Reuse. EPA/600/R-12/618. EPA/600/R-12/618.
60. Velusamy, S., Roy, A., Sundaram, S., Kumar Mallick, T., 2021. A review on heavy metal ions and containing dyes removal through graphene oxide-based adsorption strategies for textile wastewater treatment. *Chem. Rec.* 21, 1570–1610.
61. Wahiduzzaman, M., Islam, M.M., Sikder, A.H.F., Parveen, Z., 2022. Bioaccumulation and heavy metal contamination in fish species of the Dhaleswari River of Bangladesh and related human health implications. *Biol. Trace Elem. Res.* 200, 3854–3866.
62. Wahiduzzaman, M., Islam, M.M., Uddin, M.J., Al Mamun, S., Parveen, Z., n.d. Accumulation of trace metals in water and soils of tannery adjacent Dhaleshwari River of Bangladesh, subsequent transfer to local vegetables and associated human health risk.
63. Xu, X., Hu, X., Wang, T., Sun, M., Wang, L., Zhang, L., 2021. Non-inverted U-shaped challenges to regional sustainability: The health risk of soil heavy metals in coastal China. *J. Clean. Prod.* 279.