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Assessment of water quality degradation, ecological stress, and associated risks in aquatic ecosystems exposed to cigarette manufacturing effluents

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Aquatic contamination is a growing global concern due to rapid agricultural and industrial expansion. This study quantified the impacts of tobacco-manufacturing effluents on adjacent aquatic ecosystems and assessed the associated ecotoxicological risks to aquatic biota using integrated multi-index approaches. A total of 12 effluent samples were collected from a tobacco industry, along with 48 water samples from industry-adjacent crop fields (ICFs) and non-tobacco crop fields (NCFs) across four sampling campaigns conducted during the before cropping season (BCS) and after cropping season (ACS). All samples were analyzed for 28 parameters. The results demonstrated that during ICF-ACS, turbidity (94.61 ± 28.21 NTU), TSS (132.67 ± 24.40 mg L^{-1}), COD (269 ± 79.88 mg L^{-1}), BOD_5 (153 ± 59.33 mg L^{-1}), NO_3–N (18.87 ± 4.87 mg L^{-1}), PO_4–P (3.21 ± 1.12 mg L^{-1}), and major heavy metals frequently exceeded aquatic ecosystem quality (AEQ) guidelines. The chloro-alkaline indices (CAI-1 and CAI-2) indicated relatively stable ion-exchange conditions across the studied aquatic ecosystems. The water quality and health indices illustrated that values declined up to 321% from BCS to ACS, shifting suitability from 'good' to 'extremely poor', with 1.56 to 2.54-fold greater degradation in ICF waters than in NCF waters. Similarly, toxicity increased by 94.7% in ICFs compared with 52.8% in NCFs, and the Potential Ecological Risk (RI) rose to the 'very high risk' category, nearly doubling in ICFs. Hazard Quotient (HQ) analyses identified Cd, Ni, Cr, and Pb as priority contaminants in ICF waters, posing significant risks to aquatic organisms. Tobacco-manufacturing effluents significantly impaired water quality and elevated ecotoxicological risks. Implementing effective pre-discharge treatment can mitigate these impacts and safeguard the health of adjacent aquatic ecosystems.

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Environmental significance

This study highlights the significant environmental impacts of tobacco-manufacturing effluents on adjacent aquatic ecosystems. Critically elevated levels of turbidity, suspended solids, nutrients, COD, BOD_5, and heavy metals were frequently observed, exceeding aquatic ecosystem quality guidelines. Analyses of water quality and health indices revealed substantial seasonal variations further amplifying toxicity and ecological risks, with hazard quotients identifying Cd, Ni, Cr, and Pb as priority contaminants threatening aquatic organisms. Effective effluent treatment is essential to protect freshwater ecosystems, preserve aquatic life, promote sustainable agricultural practices, and advance the achievement of Sustainable Development Goals (SDGs).

1 Introduction

Since the late nineteenth century, environmental pollution has emerged as a global concern, largely driven by rapid industrialization and unregulated waste discharge.[1,2] Industrial activities contribute substantially to the estimated 7–9 billion tons of waste generated worldwide each year, with liquid effluents representing a major and persistent source of environmental contamination.[3] In developing countries, weak regulatory enforcement and inadequate treatment infrastructure have intensified the ecological consequences of industrial wastewater disposal. In Bangladesh, accelerated industrial growth over recent decades has made wastewater management a critical environmental challenge.[4–6] The industrial sector accounted for 37.56% of the national gross domestic product (GDP) in FY 2022–23,[7] with most industrial units located along riverbanks. Approximately 7000 factories discharge nearly 1.5 million m^3 of wastewater daily, contributing about 60% of total pollution nationwide.[8] Despite this scale of discharge, only 34.01% of industries operate effluent treatment plants (ETPs), exacerbating surface water degradation.[7] Among industrial sectors, tobacco (*Nicotiana tabacum* L.) manufacturing

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represents a highly resource-intensive and environmentally burdensome activity. Tobacco is cultivated in more than 124 countries, covering approximately 3.8 million ha, with major producers including China, Brazil, India, and the United States.[9] Globally, the tobacco industry generates over 200 million tons of waste annually and consumes large volumes of freshwater during processing. Major tobacco companies report annual water use ranging from 1675 to 11 247 thousand m^3, while an average of 3930 m^3 of water is required to produce one million cigarettes.[10] Consequently, tobacco-manufacturing effluents are heavily loaded with turbidity, total suspended solids (TSS), total dissolved solids (TDS), chemical oxygen demand (COD), biochemical oxygen demand (BOD_5), and nutrients.[11,12] In 2014 alone, British American Tobacco reported using more than 900 000 tons of tobacco leaves, alongside substantial quantities of paper, filters, packaging materials, adhesives, inks, tar, and cleaning agents.[13] Despite this extensive chemical footprint, the environmental impacts of tobacco manufacturing remain comparatively understudied. In Bangladesh, tobacco is the sixth most important cash crop and the second-largest agricultural export. The country ranks 14th globally in terms of tobacco cultivation area and 12th in production, contributing approximately 1.3% of the global output.[14] During FY 2021–22, tobacco cultivation covered 40 634 ha, producing 92 327 tons.[15] However, the volume and composition of effluents discharged from tobacco-manufacturing facilities remain undocumented, and their impacts on adjacent aquatic ecosystems are largely unknown. Globally, the reuse of wastewater for irrigation is increasing due to rising agricultural water demand and growing freshwater scarcity. While untreated effluent discharge has degraded soils, aquatic ecosystems, and crop quality, properly treated nutrient-rich wastewater can enhance soil fertility, improve crop yields, and support diversified cropping systems.[16,17] By 2025, more than 20 million ha worldwide are projected to rely on untreated or partially treated wastewater for irrigation.[16] In Bangladesh, increasing water demand, limited freshwater availability, and environmental quality concerns necessitate careful evaluation of industrial effluents prior to reuse. Water quality assessment for irrigation and ecosystem protection requires integrated approaches, as no single parameter sufficiently captures pollution complexity.[18] Accordingly, indices such as the Water Quality Index (WQI), Potential Ecological Risk Index (RI), Maximum Ecological Risk of Metal Quotient (MERMQ), Hazard Quotient (HQ), Hazard Index (HI), and Water Health Index (WHI) are widely used to evaluate irrigation suitability, ecological toxicity, and risks to aquatic organisms.[19,20] Along with other hydrochemical analyses, irrigation water suitability was evaluated using Soluble Sodium Percentage (SSP), Sodium Adsorption Ratio (SAR), Residual Sodium Bicarbonate (RSBC), Kelly's Ratio (KR), Magnesium Hazard (MH), Chloro-Alkaline Index-1 (CAI-1), and Chloro-Alkaline Index-2 (CAI-2).[21,22] Although several studies have also examined effluents from the textile-dyeing, tannery, pharmaceutical, fertilizer, food and beverage, and other industries in Bangladesh[5,23–31] and elsewhere, most have concentrated mainly on treatment efficiency or a limited set of water quality parameters, frequently excluding comprehensive assessments of physicochemical properties, ionic composition, and HMs.[1,32] A substantial number of national and international studies have also assessed surface and groundwater quality[18,20–22] and ecotoxicity;[33–37] these investigations have primarily focused on the hydrochemical characteristics of lakes, rivers, ponds, and aquifers for irrigation or drinking purposes, often overlooking industrial pollution and its impacts on adjacent ecosystems. In contrast, studies specifically addressing tobacco-manufacturing effluents remain scarce in the global literature,[9,11,38] and no study to date has evaluated their impacts on receiving aquatic ecosystem health in the world, including Bangladesh. Moreover, comparative assessments between tobacco-adjacent and non-tobacco-adjacent agricultural waters across seasonal variations are entirely absent in the global literature. To address this critical knowledge gap, the present study investigates water quality degradation and ecological stress in aquatic ecosystems receiving cigarette-manufacturing effluents. Specifically, it quantifies pollutant loads, identifies priority contaminants, and evaluates ecological and health risks to aquatic life using an integrated suite of indices, including irrigation water suitability indices, WQI, WHI, MERMQ, RI, HQ, and HI. The findings provide a scientific basis for targeted treatment strategies of effluents, support the safe reuse of nutrient-rich wastewater for irrigation, and contribute to the sustainable management of tobacco industrial effluents while safeguarding aquatic ecosystem health.

2 Materials and methods

2.1. Water and effluent sampling and laboratory analysis

Kushtia District, located between 23°42′–24°12′ N latitude and 88°42′–89°22′ E longitude, falls within Agro-Ecological Zone 11 (AEZ-11: High Ganges River Floodplain) and is one of the major tobacco-producing regions of Bangladesh. The district hosts extensive tobacco leaf cultivation, processing units, and cigarette-manufacturing facilities.[14] The present study was conducted in Kazihata Village (Dharmapur Union, Bheramara Upazila) and Kamalpur Village (Pairpur Union, Daulatpur Upazila) of Kushtia District (Table 1). These sites were selected due to the high prevalence of tobacco cultivation in the area (54.63%).[15] A detailed investigation was carried out at a selected cigarette-manufacturing factory after obtaining all necessary permissions from the relevant authorities. The factory discharged untreated effluents into adjacent crop fields and ponds through three drainage outlets located on the eastern, northern, and western sides, and no effluent treatment plant was in operation. A total of 12 effluent samples and 48 surface water samples were collected during four sampling campaigns covering the pre-monsoon (before the cropping season, BCS) and post-monsoon (after the cropping season, ACS) periods over two consecutive years (2024–2025). Effluent sampling was conducted exclusively during active production periods to capture peak pollution loads. To ensure representativeness, three effluent samples per season were collected directly from the drainage outlets immediately before mixing with surrounding water bodies, following established procedures.[17]

Table 1 Geographic coordinates of the study areas in the Kushtia District[a]

Sample types	Sample code	Location		Weather
		Latitude	Longitude	
Tobacco industrial effluents	TIE_1	24.031650 N	88.911155 E	Sunny
	TIE_2	24.032074 N	88.911745 E	Sunny
	TIE_3	24.031879 N	88.910792 E	Sunny
Surface water bodies in crop fields adjacent to tobacco industries	ICF_1	24.032249 N	88.917654 E	Sunny
	ICF_2	24.033180 N	88.923451 E	Sunny
	ICF_3	24.032041 N	88.925432 E	Sunny
	ICF_4	24.033791 N	88.918847 E	Sunny
	ICF_5	24.031493 N	88.921524 E	Sunny
	ICF_6	24.032327 N	88.917591 E	Sunny
Non-tobacco-crop fields adjacent to water bodies	NCF_1	24.029285 N	88.938703 E	Sunny
	NCF_2	24.031793 N	88.933942 E	Sunny
	NCF_3	24.030847 N	88.966578 E	Sunny
	NCF_4	24.009930 N	88.952495 E	Sunny
	NCF_5	24.040681 N	88.969184 E	Sunny
	NCF_6	24.029583 N	88.939414 E	Sunny

[a] TIE, tobacco industrial effluent; ICF, industry-adjacent crop fields; NCF, non-tobacco-adjacent crop field.

Surface water samples were collected from six ponds located adjacent to the factory that directly received effluent discharges. Sampling was carried out during the Rabi season because surrounding aquatic systems remain fully inundated during the monsoon, which obscures the distinct influence of industrial effluents. During the Rabi season, the factory-adjacent aquatic systems are surrounded by agricultural fields cultivated with rice, wheat, and winter maize; therefore, the ponds receive combined inputs from industrial effluents and agricultural runoff. To isolate the contribution of cigarette-manufacturing effluents, an additional 24 surface water samples were collected from non-tobacco crop fields (NCFs) using the same sampling procedures and were used as reference sites for comparison with industry-adjacent crop fields (ICFs). The selected study locations were characterized by minimal external pollution sources, being approximately 10 km from the national highway and more than 20 km from other industrial zones.[39]

All 48 surface water samples and 12 effluent samples were analyzed for 28 parameters, including physicochemical characteristics, major anions and cations, and HMs. *In situ* measurements of temperature, pH, turbidity, total dissolved solids (TDS), electrical conductivity (EC), and dissolved oxygen (DO) were conducted using a YSI Pro1030 (Xylem, USA) and a portable bench meter (HI 9813-6, Hanna Instruments, Portugal).[40] Samples for cation and anion analyses were collected in acid-washed 500 mL polyethylene bottles, sealed immediately, and preserved on ice to minimize oxidation. For HM and major cation analyses, excluding Ca^{2+} and Mg^{2+}, samples were acidified with HNO_3 (Fluka Analytical, Sigma-Aldrich, Germany) to pH < 2, transported to the laboratory within 8 h, and digested using a 1 : 3 mixture of HCl and HNO_3.[40] Concentrations of Fe, Mn, Cu, Zn, As, Pb, Cd, Cr, and Ni were determined using atomic absorption spectrophotometry (AAS; Shimadzu-7000, Japan), while Na^+ and K^+ were measured by flame photometry. Quality assurance and quality control procedures included triplicate analyses, reagent and method blanks, spike recovery tests, and determination of limits of detection. Spike recoveries ranged from 97.29% to 100.81%, indicating satisfactory analytical accuracy. Calibration curves prepared using at least five standards per element showed excellent linearity ($R^2 \geq 0.9985$).[32] Total hardness (TH), Ca^{2+}, and Mg^{2+} were determined by ethylenediaminetetraacetic acid (EDTA) titration,[34] while total suspended solids (TSS) were measured using Whatman 42 filter paper. Chemical oxygen demand (COD) was assessed using the potassium permanganate method.[34] Bicarbonate (HCO_3^-) and chloride (Cl^-) were quantified by titration following APHA guidelines,[20] whereas sulfate (SO_4^{2-}), nitrate (NO_3–N), and phosphate (PO_4–P) were analyzed using a UV–visible spectrophotometer (UV-mini-1240, Shimadzu).

2.2. Quality assurance and quality control (QA/QC) of analytical data

All laboratory analyses were conducted at the Water Research Laboratory, Institute of Environmental Science (IES), and the Central Laboratory of the University of Rajshahi, Bangladesh.

- All chemicals used in this study were of analytical grade, and all glassware was cleaned before use. Accuracy tests were conducted using standards of known concentrations to ensure the reliability of results. These tests were performed on every 10 samples to verify the calibration curve, and the percent error was calculated using eqn (1).[41]

$$\%\text{Error} = \left| \frac{C_{\text{Reported value}} - C_{\text{True value}}}{C_{\text{True value}}} \right| \times 100 \quad (1)$$

where C is the concentration in mg L^{-1}; all error values remained within ±10%, which is well within the acceptable limit of ±15%.

- Precision was evaluated by duplicate analyses, performed for every 10–20 samples in each analytical batch. The relative percent difference (RPD) between duplicates was calculated according to eqn (2).[20]

$$\%\mathrm{RPD} = \frac{M_1 - M_2}{\left(\frac{M_1 + M_2}{2}\right)} \times 100 \quad (2)$$

where M_1 and M_2 are the levels obtained for the sample and its duplicate, respectively. All RPD values remained within 10%, indicating high reproducibility.

• Method blanks, prepared by processing empty digestion vessels through all analytical steps (digestion, filtration, and dilution), were analyzed every 10 samples. All blank values were below the lower limit of quantitation (LOQ), defined as ten times the standard deviation of replicate blank measurements,[17] thereby confirming the absence of contamination from reagents.

• Spike recovery tests were carried out to evaluate potential matrix interferents. In this procedure, digested extracts were spiked with a known amount of analyte (≤2% of the sample volume), and recovery was calculated according to eqn (3).

$$\%\mathrm{Recovery} = \frac{C_{\mathrm{Spiked}} - C_{\mathrm{i}}}{C_{\mathrm{Added}}} \times 100 \quad (3)$$

where C_{Spiked} is the concentration measured in the spiked sample, C_{i} is the initial concentration in the unspiked sample, and C_{Added} is the concentration added. Recoveries for all metals were within the internationally accepted range of 85–115%.[40]

• To further ensure data quality, all samples were analyzed in triplicate. In addition, five replicate blanks were digested and analyzed to determine the limit of detection, which was found to be below 0.012 mg kg^{-1}. Calibration curves for each element were constructed using at least five standard concentrations and showed excellent linearity with coefficients of determination $R^2 \geq 0.9985$.[40]

• Data reliability was further verified by calculating the ionic charge balance between major cations and anions using eqn (4).

$$\mathrm{CBE} = \frac{\sum M_{\mathrm{c}} |N_{\mathrm{C}}| - \sum M_{\mathrm{a}} |N_{\mathrm{a}}|}{\sum M_{\mathrm{c}} |N_{\mathrm{C}}| + \sum M_{\mathrm{a}} |N_{\mathrm{a}}|} \times 100 \quad (4)$$

Here, M_{c} and N_{c} denote the molar concentration and charge of the cations, respectively, while M_{a} and N_{a} represent the corresponding values for the anions. All calculated charge balance error (CBE) values fell within the acceptable range of ±5%.[18]

2.3. Data processing and analysis

All datasets were compiled into a centralized database and statistically processed using the Statistical Package for the Social Sciences (SPSS, version 20), the R programming language (version 4.4.1), and Microsoft Excel 2016. These tools were employed to evaluate and interpret key water quality variables. Prior to Pearson correlation analysis, data normality was assessed using both the Kolmogorov–Smirnov and Shapiro–Wilk tests, which confirmed that the variables followed a normal distribution. Pearson correlation analysis was subsequently performed to examine the interrelationships among variables within the minimum data set (MDS). This analysis facilitated the identification and elimination of redundant indicators, thereby enabling the selection of the most representative variables from each MDS group while minimizing multicollinearity and information overlap. Principal component analysis (PCA) was conducted based on eigenvalues greater than 1, supported by scree plot evaluation and factor loading analysis. This approach is widely adopted in exploratory analyses involving relatively small sample sizes, where it is often preferred over the Kaiser–Meyer–Olkin (KMO) test and Bartlett's test of sphericity for assessing sampling adequacy.[41] One-way analysis of variance (ANOVA) was conducted to compare the mean values of the measured parameters among the four groups and to determine whether statistically significant differences existed at the 0.05 significance level ($p < 0.05$). A paired-sample *t*-test was also employed to examine the statistical significance of seasonal variations in 28 major water quality parameters from the BCS to the ACS, with comparisons made between ICFs and NCFs. The Water Quality Index (WQI) was employed to evaluate the water quality status of the ICF.[33,35,36] The Water Health Index (WHI) was subsequently applied to assess the ecological health of the ICF aquatic ecosystem through comparison with reference conditions at the NCF. Furthermore, the Multi-Element Risk Matrix for Quality (MERMQ) and the potential ecological Risk Index (RI) were utilized to characterize ecotoxicological risks associated with water contamination in the ICF.[37] The Hazard Quotients (HQs) and the cumulative Hazard Index (HI) were calculated to quantify the potential non-carcinogenic risks to aquatic organisms inhabiting the ICF.[35]

2.3.1. Assessment of irrigation suitability and chemical weathering using chloro-alkaline indices. No single method can comprehensively assess the suitability of surface water for irrigation.[18] Therefore, multiple indices were employed to evaluate irrigation water suitability. The parameters, including SSP, SAR, RSBC, KR, MH, and Schoeller indices (CAI-1 and CAI-2), were calculated to evaluate potential ion exchange between aquifer materials and water, all expressed in mEq L^{-1}. One-way ANOVA was performed to compare the means of these parameters, and groups showing significant differences were identified using the *post hoc* least significant difference (LSD) test.

(a) The Soluble Sodium Percentage (SSP) was calculated using eqn (5), with values below 20% considered excellent for irrigation.[17,20]

$$\mathrm{SSP} = \frac{\mathrm{Na}^+ + \mathrm{K}^+}{\mathrm{Ca}^{2+} + \mathrm{Mg}^{2+} + \mathrm{Na}^+ + \mathrm{K}^+} \times 100 \quad (5)$$

(b) The sodium adsorption ratio (SAR) was calculated using eqn (6), with values below 10 considered suitable and values above 26 considered unsuitable for irrigation.[20,21]

$$\mathrm{SAR} = \frac{\mathrm{Na}^+}{\sqrt{\frac{\mathrm{Ca}^{2+} + \mathrm{Mg}^{2+}}{2}}} \quad (6)$$

(c) The residual sodium bicarbonate (RSBC) index was calculated to assess the impact of HCO_3^- on water quality for irrigation. RSBC was computed using eqn (7). Values of RSBC below 1.25 indicate that water is suitable for agronomic use,

whereas values above 2.5 denote that water is unsuitable for such purposes.[20,21]

$$\mathrm{RSBC} = \mathrm{HCO_3^-} - (\mathrm{Ca^{2+}} + \mathrm{Mg^{2+}}) \quad (7)$$

(d) Kelly's ratio (KR) was calculated according to eqn (8) to assess water suitability for irrigation by comparing Na^+ with Mg^{2+} and Ca^{2+} concentrations. A KR value below 1 indicates that water is suitable for irrigation, whereas values above 1 reflect excessive sodium. KR values exceeding 3 denote that the water is unsuitable for irrigation purposes.[17,22]

$$\mathrm{KR} = \frac{\mathrm{Na^+}}{\mathrm{Ca^{2+}} + \mathrm{Mg^{2+}}} \quad (8)$$

(e) Excess magnesium in water can lead to alkaline soils and reduced crop yields. The magnesium hazard (MH) was calculated according to eqn (9). Values of MH greater than 50 indicate that the water is unsuitable and potentially harmful for irrigation.[18,22]

$$\mathrm{MH} = \frac{\mathrm{Mg^{2+}} \times 100}{\mathrm{Ca^{2+}} + \mathrm{Mg^{2+}}} \quad (9)$$

(f) Schoeller indices (CAI-1 and CAI-2) were calculated to evaluate potential ion exchange between aquifer materials and water during flow and residence time. The indices were computed following eqn (10) and (11).[21] Negative values of these indices indicate that K^+ and/or Na^+ have been released into water, while Mg^{2+} and Ca^{2+} have been adsorbed onto aquifer materials. Conversely, positive values suggest that alkali ions are retained by the aquifer matrix, whereas alkaline earth ions (Mg^{2+} and Ca^{2+}) are released into the water.[22] Since the pH of all studied water samples was below 8.5, the CO_3^{2-} concentration was considered negligible.[42]

$$\text{CAI-1} = \frac{\mathrm{Cl^-} - (\mathrm{Na^+} + \mathrm{K^+})}{\mathrm{Cl^-}} \quad (10)$$

$$\text{CAI-2} = \frac{\mathrm{Cl^-} - (\mathrm{Na^+} + \mathrm{K^+})}{\mathrm{HCO_3^-} + \mathrm{CO_3^{2-}} + \mathrm{SO_4^{2-}} + \mathrm{NO_3^-}} \quad (11)$$

2.3.2. WQI assessment of ICF and NCF waters for irrigation suitability and aquatic ecosystem health. The Water Quality Index (WQI) provides an integrated measure of overall water quality by aggregating the combined effects of key physicochemical and ion parameters on water suitability.[40] This index is widely employed in water quality assessment studies and is commonly calculated using eqn (12)–(14).[17] In the WQI framework, the ideal values are assumed to be zero for all parameters, except for pH (7.0) and DO (14.6 mg L^{-1}), which reflect optimal conditions for aquatic ecosystems.[34] The standard permissible limits for individual parameters were compiled from internationally recognized irrigation suitability guidelines issued by FAO,[42] Bangladesh Environmental Protection Rules (BEPR)-2023 [43] and aquatic ecosystem quality (AEQ) standards proposed by Goher *et al.*,[34] Philminaq,[44] and the US Environmental Protection Agency (US EPA),[45] with details provided in Tables 2 and 3. The quality rating (Q_i) for each parameter was calculated as

$$Q_i = \left\{\frac{|V_a - V_i|}{|V_s - V_i|}\right\} \times 100 \quad (12)$$

Here, V_a, V_s, and V_i show the measured, standard, and ideal values of the i-th parameter, respectively.

$$W_i = \frac{K}{S_i} = \frac{\frac{1}{\sum_{i=1}^{n}\left(\frac{1}{S_i}\right)}}{S_i} \quad (13)$$

Here, S_i is the standard value of the i-th parameter, n is the total number of parameters, and K is a proportionality constant ensuring normalization of the weights.

The overall WQI was then computed as

$$\mathrm{WQI} = \sum_{i=1}^{n} \frac{W_i Q_i}{\sum_{i=1}^{n} W_i} \quad (14)$$

Here, Q_i and W_i denote the quality rating and relative weight of the i-th parameter, respectively. Based on the calculated WQI values, water quality was classified into five categories: excellent (<50), good (50–100), poor (100–200), very poor (200–300), and extremely poor (>300). The extremely poor category indicates pronounced water quality deterioration, posing serious risks to aquatic biota and rendering the water unsuitable for irrigation.[20,33,36]

2.3.3. Assessment of the water health index (WHI) of ICF and NCF waters for aquatic ecosystem health. Assessment of the Water Health Index (WHI), analogous to human health evaluation, requires a comprehensive and integrative framework, as no single indicator can adequately represent ecosystem condition. The WHI combines physical, chemical, and biological attributes to provide an aggregated measure of aquatic ecosystem health.[46] In this study, PCA was applied to derive an MDS, thereby minimizing redundancy among variables and reducing analytical bias.[47] The WHI framework was used to evaluate the aquatic ecosystem health by incorporating key physical (*e.g.*, temperature, DO, and THS), chemical (*e.g.*, major anions, cations, and HMs), and biological (*e.g.*, BOD_5) indicators. A non-linear weighted scoring approach, recognized for its robustness despite greater computational complexity, was employed to integrate the selected indicators into a single index.[48] The WHI computation involved three sequential steps: (i) identification of the MDS using PCA and correlation analysis, (ii) transformation of indicators into non-linear scores, and (iii) aggregation of weighted scores to generate the final index value. Indicators were categorized according to their response behavior as either 'minimum is better' or 'optimum is better'. The scoring function was calculated using eqn (15) and (16):[39]

$$S_i = \frac{a}{\left[1 + \left(\frac{X}{X_0}\right)^b\right]} \quad (15)$$

Table 2 Statistics of physicochemical parameters and major cations of effluents and nearby waters[a]

Name of the parameters	Unit	Tobacco effluents	Industry-adjacent aquatic ecosystem		NTF-adjacent aquatic ecosystem		MPL, AEQ	*F* value	Sig. (*p*) value
		Average (mean ± SD)	BCS (mean ± SD)	ACS (mean ± SD)	BCS (mean ± SD)	ACS (mean ± SD)			
Temperature	°C	28.02 ± 2.49	25.48 ± 1.40	29.42 ± 0.91	25.30 ± 1.72	29.27 ± 1.16	8–28	17.647	0.000
Turbidity	NTU	**120.17** ± 15.47	14.84 ± 5.36	94.61 ± 28.21	17.88 ± 18.72	**57.89** ± 52.77	≤40	8.619	0.001
TSS	mg L^{-1}	**316.24** ± 44.57	**87.21** ± 7.19	**132.67** ± 24.40	**89.27** ± 17.14	**114.17** ± 18.27	25	8.852	0.001
pH	—	7.32 ± 0.24	7.79 ± 0.29	7.68 ± 0.34	7.81 ± 0.37	7.72 ± 0.43	6–9	0.155	0.925
DO	mg L^{-1}	**2.12** ± 0.27	5.58 ± 0.75	**3.19** ± 0.63	5.48 ± 0.90	**3.95** ± 1.05	≥5	11.551	0.000
COD		**487** ± 60.12	**132** ± 31.60	**269** ± 79.88	**147** ± 45.30	**206** ± 66.00	50	6.816	0.002
BOD_5		**352** ± 67.36	**62** ± 16.88	**153** ± 59.33	**69** ± 21.28	**97** ± 31.00	6	6.339	0.003
EC	µS cm^{-1}	1290 ± 178.21	848 ± 138.83	1061 ± 147.53	861 ± 424.02	912 ± 360.18	2250	0.649	0.593
TDS	mg L^{-1}	929 ± 122.72	549 ± 101.73	654 ± 110.32	597 ± 350.03	591 ± 238.21	1000	0.221	0.881
TH		**432** ± 58.24	243 ± 59.39	**324** ± 64.96	241 ± 124.35	280 ± 112.39	300	1.008	0.410
Ca^{2+}		128.17 ± 16.20	66.00 ± 20.56	95.67 ± 23.74	59.83 ± 27.41	76.33 ± 22.99	200	2.608	0.080
Mg^{2+}		27.28 ± 4.88	19.11 ± 5.73	20.66 ± 1.76	20.66 ± 14.12	21.08 ± 13.11	50	0.044	0.987
Na^{+}		19.67 ± 4.20	17.05 ± 1.36	19.65 ± 2.84	17.99 ± 2.46	21.94 ± 6.94	200	1.722	0.195
K^{+}		0.47 ± 0.16	0.58 ± 0.21	0.94 ± 0.41	0.62 ± 0.53	0.97 ± 0.57	2	1.258	0.316

[a] Bold digits indicate values exceeding the maximum permissible limits (MPLs) of aquatic ecosystem quality (AEQ), as outlined by Goher *et al.*[34] and the US EPA;[45] bold parameters show statistically significant differences ($p < 0.05$).

$$\mathrm{WQI} = \sum_{i=1}^{n} W_i \times S_i \quad (16)$$

Here, S_i is the non-linear score of the i-th indicator, W_i represents its weight derived from PCA loadings, and n is the total number of indicators included in the MDS. The parameter a denotes the maximum value of the sigmoidal function (set to 1), X is the measured value of the indicator, and X_0 represents the central tendency of the dataset. The coefficient b was set to 10.5 for 'minimum is better' indicators and to 1.0 for 'optimum is better' indicators.[47–49] Parameters such as pH, temperature, and DO were classified under the 'optimum is better' category, whereas all remaining indicators followed the 'minimum is better' criterion.[34] Based on the computed WHI values, aquatic ecosystem health was classified into five categories: very poor (<0.2), poor (0.2–0.4), moderate (0.4–0.6), good (0.6–0.8), and excellent (0.8–1.0).[20]

2.3.4. Assessment of water sample toxicity using the probability-based MERMQ index. The Multi-Element Risk Matrix for Quality (MERMQ) is a widely applied index for

Table 3 Profile of major anionic parameters and heavy metals of effluents and surrounding waters[a]

Name of the parameters	Unit	Tobacco effluents	Industry adjacent aquatic ecosystem		NTF adjacent aquatic ecosystem		MPL, AEQ	*F* value	Sig. (*p*) value
		Average (mean ± SD)	BCS (mean ± SD)	ACS (mean ± SD)	BCS (mean ± SD)	ACS (mean ± SD)			
NO_3–N	mg L^{-1}	**40.21** ± 5.30	3.85 ± 0.75	**18.87** ± 4.87	3.14 ± 1.89	**7.57** ± 4.99	7	24.039	0.000
PO_4–P		**11.46** ± 2.15	0.80 ± 0.25	**3.21** ± 1.12	0.72 ± 0.63	**1.65** ± 0.56	0.5	15.804	0.000
SO_4^{2-}		67.57 ± 10.35	54.68 ± 9.15	75.61 ± 21.63	54.31 ± 16.08	78.51 ± 50.93	309	1.206	0.333
HCO_3^{-}		**297.91** ± 38.24	204.90 ± 56.67	**222.41** ± 41.76	207.86 ± 95.69	**234.25** ± 96.19	200	0.191	0.902
Cl^{-}		31.67 ± 4.72	28.65 ± 11.59	35.53 ± 8.65	35.70 ± 31.11	38.90 ± 25.40	120	0.246	0.863
Fe		**1.008** ± 0.167	0.965 ± 0.278	**1.242** ± 0.327	1.007 ± 0.328	**1.229** ± 0.609	0.30	0.761	0.529
Mn		**0.446** ± 0.074	0.119 ± 0.053	**0.164** ± 0.065	0.117 ± 0.041	**0.129** ± 0.040	0.05	1.092	0.375
Cu		**0.079** ± 0.021	0.031 ± 0.009	**0.079** ± 0.021	0.058 ± 0.031	**0.068** ± 0.048	0.004	0.175	0.912
Zn		**0.117** ± 0.022	0.062 ± 0.025	**0.071** ± 0.023	0.030 ± 0.008	0.038 ± 0.005	0.05	20.859	0.000
As		**0.014** ± 0.007	0.012 ± 0.006	**0.020** ± 0.008	0.011 ± 0.004	**0.020** ± 0.009	0.01	3.136	0.048
Pb		**0.412** ± 0.070	0.038 ± 0.011	**0.116** ± 0.038	0.040 ± 0.015	**0.079** ± 0.059	0.0025	6.090	0.004
Cd		**0.019** ± 0.003	0.010 ± 0.004	**0.019** ± 0.007	0.011 ± 0.004	**0.015** ± 0.005	0.0018	3.644	0.030
Cr		**0.379** ± 0.062	0.074 ± 0.010	**0.114** ± 0.023	0.073 ± 0.005	**0.098** ± 0.010	0.08	12.885	0.000
Ni		**0.208** ± 0.041	0.089 ± 0.018	**0.175** ± 0.034	0.088 ± 0.016	**0.164** ± 0.042	0.052	15.081	0.000

[a] Bold digits indicate values exceeding the maximum permissible limits (MPLs) of aquatic ecosystem quality (AEQ), as outlined by Goher *et al.*;[34] Philminaq;[44] US EPA;[45] bold parameters show statistically significant differences ($p < 0.05$).

evaluating the probability of toxic effects in aquatic ecosystems arising from HM contamination.[50] The MERMQ integrates the combined influence of multiple contaminants into a single metric, facilitating the assessment of potential biological effects and the identification of areas with elevated ecological concern.[51] In this study, the MERMQ approach was employed to quantify the probability of toxicity of water samples, following eqn (17).[50]

$$\mathrm{MERMQ} = \frac{\sum_{i=1}^{n} \frac{C_n}{\mathrm{ERM}}}{n} \tag{17}$$

where C_n denotes the measured concentration of the i-th HM, ERM represents the Effects Range Median value, and n is the total number of HMs analyzed. The ERM values were adopted from aquatic ecosystem quality (AEQ) standards proposed by Goher *et al.*,[34] Philminaq,[44] and the US EPA,[45] with details provided in Tables 2 and 3. Based on the calculated MERMQ values, water samples were classified into four toxicity categories: low toxicity (<0.1; ~9% probability of adverse biological effects), medium toxicity (0.1–0.5; ~21%), high toxicity (0.5–1.5; ~49%), and very high toxicity (>1.5; ~76%), indicating progressively increasing probabilities of toxic effects on aquatic organisms.[50]

2.3.5. Evaluation of the potential ecological risk index (RI) of ICF and NCF waters. The potential ecological Risk Index (RI) is a widely used quantitative method for assessing the combined ecological risks of heavy metals (HMs) by considering their environmental sensitivity. In this study, the RI approach was applied to evaluate the potential ecological risks in industry- and NCF-adjacent aquatic ecosystems using eqn (18)–(20).[20] The RI was calculated following the method proposed by Håkanson[52] in an ecological risk index for aquatic pollution control: a sedimentological approach. In the present study, seven heavy metals (As, Cd, Pb, Cu, Zn, Cr, and Ni) were considered in the ecological risk assessment. Because the overall RI value depends on both the number of analyzed metals and their respective toxicity coefficients, the interpretation of RI values was made cautiously with reference to the original classification proposed by Håkanson.[52] The standard thresholds (RI < 150: low risk; 150–300: moderate risk; 300–600: considerable risk; RI > 600: very high risk) were used as a general guideline, while acknowledging that variations in the number and toxicity of metals may influence the cumulative RI values.

$$E_{\mathrm{r}}^{\,i} = \sum_{i=1}^{n} \left(T_{\mathrm{r}}^{\,i} \times C_{\mathrm{f}}^{\,i} \right) \tag{18}$$

$$C_{\mathrm{f}}^{\,i} = \frac{C_n}{B_n} \tag{19}$$

$$\mathrm{RI} = \sum_{i=1}^{n} E_{\mathrm{r}}^{\,i} \tag{20}$$

where $T_{\mathrm{r}}^{\,i}$ denotes the toxic-response coefficient of the i-th HM, $C_{\mathrm{f}}^{\,i}$ represents the contamination factor, C_n is the measured concentration of the heavy metal, and B_n is the corresponding reference or standard value. The term $E_{\mathrm{r}}^{\,i}$ refers to the individual ecological risk factor for the given parameters, and n is the total number of HMs considered. The toxic-response coefficients used in this study were adopted from Kowalska *et al.*[50] and were as follows: Cd = 30, As = 10, Cu = 5, Ni = 5, Pb = 5, Cr = 2, and Zn = 2. Based on the calculated $E_{\mathrm{r}}^{\,i}$ values, ecological risk (ER) was classified into five categories: low (<40), moderate (40–80), considerable (80–160), high (160–320), and very high (≥320).[52,53]

2.3.6. Health risk assessment of aquatic organisms in ICF and NCF waters using the HQ and HI. The Risk Quotients (RQs), also referred to as Hazard Quotients (HQs), were determined according to eqn (21).[25]

$$\mathrm{HQ} = \frac{\mathrm{MEC}}{\mathrm{PNEC}} \tag{21}$$

where MEC denotes the measured environmental concentration of each target analyte (expressed in mg L^{-1}) and PNEC represents the predicted no-effect concentration (mg L^{-1}), a substance-specific threshold below which adverse effects are not expected to occur. To evaluate the combined hazards posed by multiple HMs in water, the Hazard Index (HI) was computed as the sum of individual MEC/PNEC ratios, following the widely adopted approach (eqn (22)) described by Yang-Guang.[54] This cumulative risk metric is extensively utilized in ecological hazard assessments to characterize potential adverse effects arising from complex mixtures of contaminants.

$$\mathrm{HI} = \sum_{i=1}^{n} \mathrm{HQ}_i = \sum_{i=1}^{n} \frac{\mathrm{MEC}_i}{\mathrm{PNEC}_i} \tag{22}$$

The calculated HQ and HI values were classified into four risk categories: no health hazard (HI < 0.1), low health hazard (0.1 ≤ HI ≤ 1.0), moderate health hazard (1.1 ≤ HI ≤ 10), and high health hazard to aquatic organisms (HI > 10), following the classification scheme proposed by Kaewrat *et al.*[55]

3 Results and discussion

Cigarette-manufacturing effluents in Bangladesh contain elevated concentrations of heavy metals (HMs) and toxic pollutants (Tables 2 and 3) that pose serious threats to aquatic ecosystems. The continuous discharge of these effluents into canals, rivers, and ponds deteriorates water quality, disrupts ecological processes, and accelerates habitat degradation. Consequently, aquatic biodiversity is increasingly at risk, with potential long-term implications for the integrity and sustainability of ecosystems. Because industry-adjacent aquatic ecosystems are affected by multiple pollution sources, including both cigarette-manufacturing effluents and agricultural runoff, the specific contribution of industrial activities to pollutant loading in the industry-adjacent crop field (ICF) cannot be determined in isolation. To address this limitation, a comparative assessment was conducted with the non-tobacco crop field (NCF) aquatic ecosystems. This approach enables clearer differentiation between industry-related contamination and background agricultural inputs, allowing more confident attribution of observed pollutant variations to industrial influence and providing a realistic evaluation of the additional

environmental burden associated with proximity to cigarette-manufacturing activities.

3.1. Comparative analysis of aquatic ecosystems in tobacco industry-adjacent crop fields (ICFs) with reference to non-tobacco crop fields (NCFs)

To evaluate the impacts of cigarette-manufacturing effluents on adjacent aquatic ecosystems, water samples were collected from tobacco ICFs and NCFs during both the BCS and ACS periods over two consecutive years. The results were evaluated against baseline aquatic ecosystem quality (AEQ) standards adopted from Goher *et al.*[34] Philminaq,[44] and the US EPA,[45] with summarized data presented in Tables 2 and 3. During the BCS (post monsoon period), most water quality parameters exhibited comparable values in both field types, likely due to widespread monsoon submergence that reduced spatial variability and diluted pollutant concentrations. In contrast, during the ACS (pre-monsoon period), the majority of parameters increased in both ecosystems, with several exceeding the MPLs of AEQ standards. The greater level of degradation in ICFs can be attributed to the combined influence of industrial effluent discharge and agricultural runoff, whereas in NCFs, water quality impairment was driven exclusively by agricultural activities.

3.1.1. Comparison of physicochemical parameters and major cations between ICF and NCF waters. Table 2 presents a comparative summary of physicochemical parameters and major cations in the aquatic ecosystems of both fields during the BCS and ACS periods. One-way analysis of variance (ANOVA) revealed that temperature, turbidity, TSS, DO, COD, and BOD_5 exhibited significantly different mean values among the groups at the 0.05 significance level ($p < 0.05$). This indicates that these parameters were substantially influenced by pollutant inputs during the ACS periods in both fields, whereas the remaining parameters did not show statistically significant differences among the groups (Table 2). Across all sampling sites, temperature and pH remained within aquatic ecosystem quality (AEQ) standards, although waters during the ACS were slightly warmer than those in the BCS. This variation reflects seasonal influences, as the BCS corresponds to the cooler post monsoon winter period, whereas the ACS occurs during the warmer pre-monsoon season. Turbidity and total suspended solids (TSS), which are key indicators of water quality associated with suspended particles, fine plant debris, organic matter, plankton, and potential pathogens,[56] increased markedly from the BCS to the ACS at both sites. However, values recorded at industry-adjacent sites during the ACS (94.61 ± 28.21 NTU and 132.67 ± 24.40 mg L^{-1}) were substantially higher than those observed at NCF-ACS sites (57.89 ± 52.77 NTU and 114.17 ± 18.27 mg L^{-1}) and exceeded AEQ thresholds, indicating enhanced particulate loading linked to industrial effluent inputs. Dissolved oxygen (DO) declined at all sites during the ACS, with the most pronounced depletion observed in industry-adjacent waters (3.19 ± 0.63 mg L^{-1}), falling below the AEQ guideline of 5 mg L^{-1}. In comparison, DO levels in NCF-ACS waters were slightly higher (3.95 ± 1.05 mg L^{-1}) but still indicative of ecological stress. Indicators of organic pollution, including chemical oxygen demand (COD) and biochemical oxygen demand (BOD_5), increased sharply from the BCS to the ACS. Industry adjacent ACS sites exhibited particularly elevated concentrations (COD: 269 ± 79.88 mg L^{-1} and BOD_5: 153 ± 59.33 mg L^{-1}), nearly twice those measured in NCF-ACS waters and far exceeding AEQ permissible limits. Salinity-related parameters, including electrical conductivity (ECw), total dissolved solids (TDS), total hardness (TH), and all measured cations, also increased after the cropping season in both fields. Nevertheless, these parameters remained within AEQ limits. Comparable patterns of excessive turbidity, TSS, COD, and BOD_5 accompanied by reduced DO have been reported in aquatic ecosystems adjacent to textile-dyeing industries,[32] tanneries,[17] and pulp and paper industries,[30] lending further support to the trends observed in the present study. Hussain *et al.*[35] reported elevated BOD and reduced DO levels in the Buriganga River and Turag River adjacent to tanning industries, findings that are consistent with the results of the present study. The analysis of tobacco-industrial effluents also revealed excessively high levels of turbidity, TSS, COD, and BOD_5, accompanied by critically low DO concentrations (Table 2), indicating that a substantial proportion of these pollutants in adjacent aquatic systems originates from tobacco manufacturing discharges. Globally, including in Bangladesh, studies directly assessing water quality in aquatic environments adjacent to tobacco industries remain extremely limited. However, investigations of tobacco wastewater by Adenike[11] and Zhu *et al.*[38] reported similarly elevated concentrations of these parameters in tobacco industry effluents, thereby corroborating the findings of the present study and reinforcing the attribution of observed water quality deterioration to tobacco industrial activities.

Ahmed *et al.*[57] reported that the optimal water temperature for carp ranges from 24 to 30 °C, indicating that aquatic conditions in both study fields remained within a suitable thermal range. In contrast, elevated turbidity and TSS observed in both ecosystems, driven by nutrient and organic matter-induced algal blooms and fine plant particulates (<200 μm) transported by runoff, can adversely affect aquatic systems. These conditions reduce light penetration, constrain photosynthetic activity, and increase disease susceptibility among aquatic organisms.[58] The decomposition of organic matter contributed to elevated COD and BOD_5 in both ecosystems, resulting in a corresponding decrease in DO. For cyprinid species, optimal COD concentrations in pond and river waters range between 20 and 30 mg L^{-1}, while acceptable BOD_5 levels vary from 8 to 15 mg L^{-1} depending on culture intensity and reaeration conditions. Bhatnagar and Devi[59] further noted that BOD_5 values of 3 to 6 mg L^{-1} support normal aquatic activity, whereas concentrations exceeding 12 mg L^{-1} may induce fish mortality through oxygen depletion. Similarly, DO concentrations below the critical threshold of 5 mg L^{-1} impair the growth, survival, distribution, and physiological functioning of aquatic organisms.[40] Overall, water quality deteriorated from the BCS to the ACS across both fields, with industry-adjacent sites exhibiting greater departures from AEQ standards. The most

pronounced impacts were observed in DO, organic pollution indicators including turbidity, TSS, COD, and BOD_5, and ionic enrichment, as reflected by TH. These results underscore the substantially higher ecological stress imposed by cigarette-manufacturing effluents compared with NCF ecosystems.

3.1.2. Comparative statistics of major anions and heavy metals between ICF and NCF waters. One-way analysis of variance (ANOVA) of anions and HMs revealed that only NO_3–N and PO_4–P among the major anions and Zn, Pb, Cd, Cr, and Ni among the HMs exhibited significant differences among the groups at the 0.05 significance level ($p < 0.05$). This suggests that these parameters were markedly influenced by pollutant inputs during the ACS periods in both fields, whereas the remaining parameters showed no statistically significant variation among the groups (Table 3). The comparative results also illustrated that NO_3–N markedly increased from (3.85 ± 0.75) to (18.87 ± 4.87) mg L^{-1} in the ICF and from (3.14 ± 1.89) to (7.57 ± 4.99) mg L^{-1} in the NCF. Similarly, PO_4–P rose from (0.80 ± 0.25) to (3.21 ± 1.12) mg L^{-1} in the ICF and from (0.72 ± 0.63) to (1.65 ± 0.56) mg L^{-1} in the NCF (Table 3). These pronounced increases over the study period resulted in concentrations exceeding the recommended AEQ standards in both fields. Notably, the increases in NO_3–N and PO_4–P in the ICF were more than double, approximately 2.6–3.4 times higher than those observed in the NCF, indicating substantially greater nutrient enrichment in industry-adjacent ecosystems.

Bicarbonate (HCO_3^-) concentrations also exceeded AEQ standards in both fields, although the magnitude of increase was comparable between the ICF and NCF. In contrast, sulfate (SO_4^{2-}) and chloride (Cl^-) showed modest increases during the ACS in both fields; however, these changes were not statistically significant and remained below AEQ guideline limits. Collectively, these patterns indicate that the pronounced enrichment of NO_3–N and PO_4–P in the ICF is largely attributable to inputs from tobacco industry effluents. This inference is supported by earlier studies reporting elevated NO_3–N and PO_4–P concentrations in tobacco industrial wastewater,[11] national and international river water,[33,35] and effluents from other industrial sectors,[16,30] reinforcing the role of industrial discharge as a major source of nutrient loading in adjacent aquatic systems.

Nitrate (NO_3^-) and phosphate (PO_4^{3-}) are essential nutrients for primary producers; however, excessive inputs accelerate eutrophication by stimulating algal and phytoplankton blooms, including harmful algal blooms capable of toxin production.[59] Dense blooms reduce light penetration, impair submerged vegetation, and degrade associated habitats. Subsequent algal decay consumes DO, leading to hypoxic or anoxic conditions that cause mortality of sensitive taxa and favor more tolerant species, ultimately altering the food web structure.[42] Elevated nitrate further interacts with sediments, influencing phosphorus release, while overall nutrient over-enrichment degrades water quality in terms of clarity, odor, and taste and disrupts nitrogen and phosphorus cycling.[59] In addition to nutrient enrichment, all analyzed HMs exceeded recommended AEQ standards in both field types, with consistently higher concentrations in the ICF than in the NCF, indicating more severe contamination in industry-adjacent ecosystems. This trend aligns with effluent characterization results, which also revealed elevated Mn, Pb, Cd, Cr, and Ni concentrations (Table 3), underscoring tobacco industry effluents as a major source of HM loading. Similar patterns of HM enrichment in industrial effluents and nearby water bodies have been widely reported, including tobacco sludge,[9,60] tanneries,[17] pharmaceutical industries,[19] textile dyeing industries,[25,61] personal care product industries,[25] Huaihe River in China and Manchar Lake in Pakistan.[35] Such enrichment accelerates ecological degradation, as elevated Mn impairs gill function and reduces invertebrate diversity, Zn disrupts enzymatic activity and photosynthesis, Pb bioaccumulates, causing neurological and reproductive disorders, and Cd damages gills and kidneys while reducing benthic survival. Likewise, hexavalent Cr exerts carcinogenic and mutagenic effects by altering microbial processes, and Ni interferes with osmoregulation and suppresses growth and reproduction in aquatic organisms.[56–58] In summary, the findings demonstrate that tobacco industry effluents substantially elevate nutrients (NO_3^- and PO_4^{3-}) and HM (Zn, Pb, Cd, Cr, and Ni) concentrations in adjacent aquatic ecosystems, driving eutrophication, organic pollution, and metal-induced toxicity, which collectively degrade water quality, disrupt ecological functions, and impose greater environmental stress on the ICF compared with NCF aquatic ecosystems.

3.2. Comparative analysis of changes in water quality parameters from BCS to ACS

To quantitatively assess the greater increases observed in the ICF compared with the NCF, a paired sample *t*-test was conducted to evaluate the statistical significance of seasonal changes in 28 major water quality parameters from the BCS to the ACS.[39] This analysis enables a robust differentiation of temporal variations between industry-adjacent and NTF-adjacent aquatic ecosystems, thereby quantifying the relative contribution of effluents to pollutant loading. The paired mean differences, SD, 95% confidence intervals (CIs), calculated *t*-values, and significance levels ($p \leq 0.05$) are presented in Table 4, with statistically significant differences highlighted in bold.

The results revealed that several physicochemical parameters, including turbidity, TSS, COD, BOD_5, EC, TDS, and TH, exhibited statistically significant increases in the ICF relative to the NCF. Likewise, key ionic parameters, such as Ca^{2+}, NO_3^-, and PO_4^{3-}, and heavy metals, including Mn, Zn, Pb, Cd, Cr, and Ni, were significantly elevated in the ICF. Conversely, DO levels decreased significantly in the ICF, indicating potential stress on aquatic organisms. Some parameters, including temperature and Fe and Cu concentrations, were higher in the ICF, whereas pH, Mg^{2+}, K^+, SO_4^{2-}, HCO_3^-, Cl^-, and As were higher in the NCF; however, these differences were not statistically significant. The paired mean differences (MDs) were particularly pronounced for turbidity (36.71 ± 41.23 NTU), TSS (18.50 ± 11.64 mg L^{-1}), COD (63.17 ± 82.19 mg L^{-1}), BOD_5 (45.12 ± 57.90 mg L^{-1}), EC (149.17 ± 307.16 μS cm^{-1}), TDS (63.36 ± 193.32 mg L^{-1}), TH (43.67 ± 98.03 mg L^{-1}), Ca^{2+} (19.33 ± 20.80 mg L^{-1}), NO_3^- (11.29 ± 4.55 mg L^{-1}), and PO_4^{3-} (1.56 ± 0.91 mg L^{-1}), highlighting a substantial elevation in the ICF

Table 4 Paired samples *t*-test of water parameters increases between ICF and NCF waters[a]

Paired samples test								
		Paired differences from ICFs to NCFs						
				95% CI				
Paired parameters (ICFs *vs.* NCFs)		Mean	Standard deviation	Lower	Upper	Calculated *t*-value	df	Significant at the 5% level (2-tailed)
Pair 1	Tem–Tem	0.15	1.27	−1.18	1.48	0.290	23	0.783
Pair 2	Tur–Tur	36.71	41.23	−6.55	79.98	**2.181**	23	0.081
Pair 3	TSS–TSS	18.50	11.64	6.28	30.72	**3.893**	23	0.011
Pair 4	pH–pH	−0.04	0.50	−0.56	0.49	−0.188	23	0.858
Pair 5	DO–DO	−0.75	1.27	−2.09	0.59	**−1.444**	23	0.208
Pair 6	COD–COD	63.17	82.19	−23.09	149.42	**1.883**	23	0.118
Pair 7	BOD_5–BOD_5	45.12	57.90	−15.65	105.88	**1.909**	23	0.115
Pair 8	EC–EC	149.17	307.16	−173.18	471.51	**1.190**	23	0.288
Pair 9	TDS–TDS	63.36	193.32	−139.53	266.24	**0.803**	23	0.459
Pair 10	TH–TH	43.67	98.03	−59.21	146.54	**1.091**	23	0.325
Pair 11	Ca^{2+}–Ca^{2+}	19.33	20.80	−2.50	41.16	**2.277**	23	0.072
Pair 12	Mg^{2+}–Mg^{2+}	−0.42	12.66	−13.71	12.87	−0.082	23	0.938
Pair 13	Na^{+}–Na^{+}	−2.28	8.06	−10.74	6.18	**−0.693**	23	0.519
Pair 14	K^{+}–K^{+}	−0.03	0.68	−0.74	0.68	−0.102	23	0.923
Pair 15	NO_3^{-}–NO_3^{-}	11.29	4.55	6.51	16.07	**6.074**	23	0.002
Pair 16	PO_4^{3-}–PO_4^{3-}	1.56	0.91	0.60	2.51	**4.189**	23	0.009
Pair 17	SO_4^{2-}–O_4^{2-}	−2.91	56.72	−62.43	56.62	−0.125	23	0.905
Pair 18	HCO_3^{-}–HCO_3^{-}	−11.84	88.58	−104.80	81.12	−0.327	23	0.757
Pair 19	Cl^{-}–Cl^{-}	−3.37	21.47	−25.91	19.16	−0.385	23	0.716
Pair 20	Fe–Fe	0.013	0.52	−0.53	0.56	0.061	23	0.954
Pair 21	Mn–Mn	0.035	0.07	−0.04	0.11	**1.169**	23	0.295
Pair 22	Cu–Cu	0.003	0.06	−0.06	0.06	0.105	23	0.920
Pair 23	Zn–Zn	0.041	0.02	0.02	0.07	**4.353**	23	0.007
Pair 24	As–As	0.000	0.01	−0.01	0.01	−0.067	23	0.949
Pair 25	Pb–Pb	0.036	0.06	−0.02	0.10	**1.534**	23	0.186
Pair 26	Cd–Cd	0.005	0.00	0.00	0.01	**2.314**	23	0.069
Pair 27	Cr–Cr	0.017	0.03	−0.01	0.05	**1.480**	23	0.199
Pair 28	Ni–Ni	0.011	0.04	−0.04	0.06	**0.585**	23	0.584

[a] Bold values indicate significant increases in water parameters between the industry-adjacent crop field (ICF) and the non-tobacco crop field (NCF); Tem, temperature; Tur, turbidity; and CI, confidence interval.

relative to the NCF. These results substantiate the earlier descriptive analyses and confirm that aquatic ecosystems adjacent to tobacco industry-associated crop fields experience significantly higher levels of those contaminants.

Overall, the findings indicate that ICF ecosystems are considerably more polluted than NCF ecosystems, with elevated levels of physicochemical parameters (turbidity, TSS, COD, BOD_5, EC, TDS, and TH), nutrients (Ca^{2+}, NO_3^{-}, and PO_4^{3-}), and heavy metals (Mn, Zn, Pb, Cd, Cr, and Ni) posing substantial ecological risks, including reduced water quality and potential toxicity to aquatic organisms. These observations underscore the substantial environmental impact of cigarette-manufacturing effluents on adjacent water bodies and highlight the urgent need for rigorous effluent management and regulatory interventions to safeguard aquatic ecosystems.

3.3. Irrigation water suitability and potential ion exchange in ICF and NCF waters

Table 5 presents the assessment of irrigation water suitability for the industry-adjacent aquatic ecosystem (IAE) and the non-tobacco adjacent aquatic ecosystem (NAE) during the before cropping season (BCS) and after cropping season (ACS) using several hydrochemical indices. The Soluble Sodium Percentage (SSP) ranged from 3.00 to 18.78%, indicating that all samples were suitable for irrigation. Comparatively lower mean SSP values were observed during the ACS in both ecosystems, suggesting a reduced contribution of Na^{+} and a relatively higher dominance of Ca^{2+} during the cropping period. Similarly, the Sodium Adsorption Ratio (SAR) exhibited a narrow range (0.235–0.609), with lower mean values in ACS compared with BCS, indicating a decrease in sodium hazard following the cropping season. Both the SSP and SAR results demonstrated that all water samples were suitable for irrigation during BCS, while water quality further improved in ACS. In contrast, Residual Sodium Bicarbonate (RSBC) showed relatively wider variability (−14.87 to 10.98), reflecting fluctuations in bicarbonate concentrations influencing irrigation water chemistry. Although the waters remained suitable for irrigation during BCS, RSBC values increased markedly during ACS, rendering some samples unsuitable for irrigation. Kelly's Ratio (KR) and Magnesium Hazard (MH) also displayed seasonal variation, with all samples remaining within the suitable range during

Table 5 Irrigation water suitability assessment using SSP, SAR, RSBC, KR, MH, CAI-1, and CAI-2 indices and the corresponding one-way ANOVA results ($n = 24$)[a]

Name of the index	Name of the field	Minimum	Maximum	Mean	Std. deviation	Std. error	*F* value	Sig. (*p*) value
Soluble sodium percentage (SSP)	IAE-BCS	10.11	18.68	14.00	3.35	1.37	17.854	0.000
	IAE-ACS	3.00	9.42	5.37	2.42	0.99		
	NAE-BCS	9.50	18.78	15.87	3.60	1.47		
	NAE-ACS	3.64	8.81	7.61	1.97	0.80		
Sodium adsorption ratio (SAR)	IAE-BCS	0.386	0.582	0.486	0.081	0.033	15.191	0.000
	IAE-ACS	0.235	0.403	0.300	0.067	0.027		
	NAE-BCS	0.441	0.609	0.532	0.058	0.024		
	NAE-ACS	0.315	0.477	0.380	0.054	0.022		
Residual sodium bicarbonate (RSBC)	IAE-BCS	−1.513	0.409	0.167	−2.172	−1.129	6.213	0.004
	IAE-ACS	−14.827	8.380	3.421	−26.553	−5.309		
	NAE-BCS	−1.284	1.184	0.483	−3.176	−0.261		
	NAE-ACS	−10.534	10.198	4.163	−30.393	−4.591		
Kelley's ratio (KR)	IAE-BCS	0.161	0.045	0.019	0.109	0.225	16.752	0.000
	IAE-ACS	0.056	0.027	0.011	0.030	0.101		
	NAE-BCS	0.187	0.049	0.020	0.101	0.226		
	NAE-ACS	0.081	0.022	0.009	0.036	0.096		
Magnesium hazard (MH)	IAE-BCS	32.794	8.685	3.546	20.726	42.994	20.747	0.000
	IAE-ACS	11.117	5.067	2.069	5.838	18.880		
	NAE-BCS	34.493	8.205	3.350	25.742	47.592		
	NAE-ACS	13.070	3.456	1.411	8.774	18.043		
Chloro-alkaline index (CAI-1)	IAE-BCS	−0.104	0.517	0.211	−0.845	0.423	0.454	0.718
	IAE-ACS	0.100	0.135	0.055	−0.025	0.246		
	NAE-BCS	−0.179	0.613	0.250	−0.895	0.621		
	NAE-ACS	−0.027	0.300	0.122	−0.491	0.425		
Chloro-alkaline index (CAI-2)	IAE-BCS	0.001	0.075	0.031	−0.100	0.090	0.059	0.981
	IAE-ACS	0.016	0.021	0.008	−0.003	0.038		
	NAE-BCS	0.017	0.122	0.050	−0.089	0.206		
	NAE-ACS	0.007	0.056	0.023	−0.058	0.109		

[a] IAE, industry adjacent aquatic ecosystem; NAE, non-tobacco field adjacent aquatic ecosystem; BCS, before the cropping season; ACS, after the cropping season; bold parameters show statistically significant differences ($p < 0.05$).

BCS and showing further improvement during ACS. This improvement is likely associated with an increased contribution of Ca^{2+} to the aquatic systems relative to Na^{+} and Mg^{2+} during the cropping season, possibly linked to agricultural inputs such as calcium-based fertilizers, particularly gypsum. In contrast, the Chloro-Alkaline Indices (CAI-1 and CAI-2) showed relatively minor variation among sampling groups, suggesting limited ion-exchange processes between water and surrounding geological materials. Although significant values of CAI-1 and CAI-2 have been reported for groundwater systems by Ekbal and Khan[21] and Ghobadi *et al.*[22] the present study focused exclusively on surface water samples. In surface aquatic environments, the interaction between water and geological materials is generally limited compared with groundwater systems. Consequently, only minimal contributions from surrounding rocks and minerals were expected, resulting in comparatively weak water–rock interactions. This hydrogeochemical setting likely explains the non-significant CAI-1 and CAI-2 values observed in the studied samples, indicating negligible ion-exchange processes within the investigated aquatic ecosystems. One-way ANOVA results indicated that SSP, SAR, RSBC, KR, and MH differed significantly among the four sampling groups ($p < 0.05$), with *F*-values ranging from 6.213 to 20.747, demonstrating that seasonal agricultural activities exerted a measurable influence on irrigation water quality. However, CAI-1 and CAI-2 did not show statistically significant differences ($p > 0.05$), indicating relatively stable ion-exchange conditions across the studied aquatic ecosystems. Post-hoc Least Significant Difference (LSD) tests further revealed no statistically significant differences between IAE-BCS and NAE-BCS or between IAE-ACS and NAE-ACS for most indices, whereas significant differences were observed between BCS and ACS within each ecosystem (IAE-BCS *vs.* IAE-ACS and NAE-BCS *vs.* NAE-ACS). These findings indicate that seasonal agricultural practices, rather than tobacco industrial effluents, primarily influenced variations in irrigation water quality indices. Overall, the results suggest that agricultural activities tended to improve several indices (SSP, SAR, KR, and MH), although RSBC showed deterioration during ACS. Collectively, these findings demonstrate that seasonal agricultural inputs can influence key hydrochemical indices of irrigation water suitability, while ion-exchange characteristics remain comparatively stable and unaffected by nearby tobacco industrial activities.

3.4. Impact of cigarette-manufacturing effluents on the surrounding water quality in ICFs

Fig. 1 illustrates the variation in Water Quality Index (WQI) values for both irrigation water quality (IWQ) and aquatic

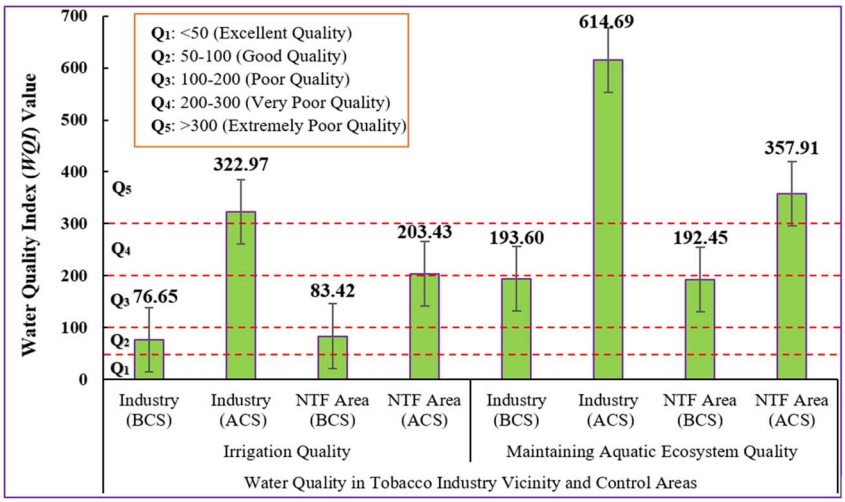

Fig. 1 Comparison of irrigation suitability and aquatic ecosystem quality between ICF and NCF waters.

ecosystem quality (AEQ) in the industry-adjacent crop fields (ICFs) and non-tobacco crop fields (NCFs) during the before cropping season (BCS) and after cropping season (ACS). Overall, the results demonstrate clear seasonal deterioration in water quality in both ecosystems, although the magnitude of degradation was considerably higher in the industry-influenced environment. For irrigation suitability, WQI values exhibited pronounced seasonal variation across the two field types. In ICFs, irrigation water quality declined markedly from the 'good' category during BCS (76.65) to the 'extremely poor' category during ACS (322.97), indicating substantial deterioration during the cropping period. In contrast, NCFs retained comparatively better irrigation quality, shifting from 'good' in BCS (83.42) to 'very poor' in ACS (203.43), suggesting that although degradation occurred, it was primarily associated with agricultural activities rather than industrial inputs. Quantitatively, irrigation water quality deteriorated by 321.36% in ICFs compared with 143.86% in NCFs, indicating that the magnitude of degradation in the industry-adjacent system was approximately 2.04 times greater. This elevated deterioration in ICFs is likely attributable to the combined influence of agricultural runoff and cigarette-manufacturing effluents, which can introduce a range of pollutants into nearby aquatic environments. Among the analyzed parameters, turbidity, PO_4–P, DO, NO_3–N, K^+, and BOD_5 emerged as the principal contributors to irrigation water degradation. Comparable deterioration of surface and irrigation water quality in industrial regions has been reported in several studies. For instance, Jiku *et al.*[16] documented significant surface water degradation in the industrial zones of Gazipur and Savar in Bangladesh, while Monira *et al.*[17] reported substantial deterioration of irrigation water quality around the Savar Tannery Estate. Similarly, Hossain *et al.*[35] highlighted poor irrigation water conditions in tannery-dominated industrial areas worldwide. These observations are consistent with the present findings and reinforce the evidence that industrial activities can substantially impair water quality in adjacent agricultural landscapes.

A comparable trend was observed for aquatic ecosystem quality (AEQ). In ICFs, the WQI value increased sharply from 193.60 (poor quality) during BCS to 614.69 during ACS, placing the ecosystem well within the 'extremely poor' category. Such a dramatic increase indicates severe ecological degradation and reflects the cumulative effects of industrial effluent discharge and crop-field runoff during the cropping season. In NCFs, although the WQI values were comparatively lower, they still indicated notable ecological stress, increasing from 192.45 (poor) in BCS to 357.91 (extremely poor) in ACS (Fig. 1). Quantitatively, aquatic ecosystem quality deteriorated by 217.50% in ICFs compared with 85.98% in NCFs, demonstrating that degradation in the industry-adjacent ecosystem was approximately 2.54 times greater. The higher deterioration in ICFs is likely linked to the discharge of cigarette-manufacturing effluents, which can substantially elevate nutrient loads and organic pollutants in surrounding aquatic systems. Among the assessed parameters, PO_4–P, BOD_5, NO_3–N, DO, K^+, and TSS were identified as the most influential contributors to ecosystem degradation, while other parameters played comparatively minor roles. Similar deterioration of aquatic ecosystems has been reported in other industrially influenced water bodies, including the Nile River in Egypt reported by Goher *et al.*[34] and aquatic systems in the Black Sea region documented by Tokatli *et al.*,[37] which supports the trends observed in the present study.

From an ecological perspective, elevated WQI values indicate increased pollutant concentrations, oxygen depletion, and physicochemical imbalances in aquatic environments. Such conditions can impose significant physiological stress on aquatic organisms, impairing growth, reproduction, and survival, and may ultimately lead to reduced biodiversity, altered community structure, and ecosystem instability.[20,36] Although seasonal deterioration was evident in both field types, the intensity of degradation was markedly greater in the industry-adjacent ecosystem, highlighting the substantial ecological pressure associated with tobacco-industry effluents. Overall, the results indicate that crop fields located near

cigarette-manufacturing industries experience considerably greater degradation in both irrigation water quality and aquatic ecosystem quality compared with non-tobacco agricultural areas. Notably, the magnitude of deterioration was more pronounced for aquatic ecosystem quality than for irrigation water quality. Among the evaluated parameters, PO_4–P, BOD_5, NO_3–N, DO, K^+, turbidity, and TSS were identified as the primary drivers of water quality decline. These findings emphasize the importance of implementing effective wastewater treatment and pollution-control strategies in cigarette-manufacturing industries to reduce pollutant loads and safeguard both irrigation resources and the ecological integrity of surrounding aquatic ecosystems.

3.5. Impact of cigarette-manufacturing effluents on the aquatic ecosystem health around ICFs

The Water Health Index (WHI) offers a comprehensive framework for assessing aquatic ecosystem health by integrating advanced statistical techniques with a carefully selected minimum dataset (MDS). It was developed to facilitate sectoral comparisons and to evaluate broader ecological risks to aquatic organisms through the combined consideration of physical, chemical, biological, and heavy metal indicators.[20,48] Key pollutant groups were identified using PCA, where each principal component (PC) represents a distinct source. PCs with eigenvalues ≥1.0 and explaining at least 5% of the total variance were retained,[47] with eigenvalues indicating the variance captured and variance percentages reflecting individual contributions.

PCA was performed using a rotated component matrix with Varimax rotation and Kaiser normalization to enhance interpretability.[39] Four significant PCs met the selection criteria, collectively explaining 83.35% of the total variance (Table 6). To minimize redundancy, variables were selected based on factor loadings within 10% of the maximum loading in each PC and statistically significant correlations ($p \leq 0.05$) derived from the correlation matrix (Table 7) following Martin-Sanz *et al.*[49] The retained PCs had eigenvalues of 9.959, 9.285, 2.103, and 1.990, with corresponding PC weights (W_i) of 0.427, 0.398, 0.090, and 0.085, respectively. In PC_1, although Cr, TSS, NO_3^-, PO_4^{3-}, Zn, and Ni showed high variability, Cr was selected due to its dominant loading and strong positive correlations with the remaining variables. Similarly, Cl^- was selected from PC_2, Mn from PC_3, and Fe from PC_4 based on the same criteria. Consequently, the final MDS for WHI assessment comprised Cr, Cl^-, Mn, and Fe, along with their respective PC weights.

Aquatic ecosystem health in the vicinity of tobacco manufacturing areas was evaluated during both before the cropping season (BCS) and after the cropping season (ACS), with comparisons made against non-tobacco crop field (NCF) areas (Fig. 2). During the BCS, the WHI values indicated excellent aquatic health in industry-adjacent crop fields (0.866), while NCF waters exhibited good conditions (0.692). In contrast, a pronounced deterioration was observed during the ACS, with the WHI values declining to 0.236 in ICFs and 0.288 in NCFs, classifying both sites as 'very poor'. The absolute reduction in the WHI was 0.630 in ICFs and 0.404 in NCFs, indicating that degradation in ICFs was 1.56 times greater than that in NCFs. Proportionally, the WHI declined by 72.75% in ICFs compared to 58.38% in NCFs, underscoring the heightened vulnerability of industry-adjacent aquatic systems to seasonal pressures. Although both sites experienced substantial post-cropping deterioration, the markedly greater decline in ICFs highlights the additional influence of tobacco-manufacturing effluents beyond agricultural activities alone. The WHI proved more sensitive and discriminative than the WQI, as the latter is limited to physicochemical, anionic, and cationic parameters, whereas the WHI incorporates HMs alongside conventional indicators. Consistent with recent studies across multiple industrial sectors, inadequately treated industrial effluents represent a major source of HMs and organic loads that degrade freshwater quality and disrupt aquatic ecosystem health.[6,24,26,27,29,31] The 1.56-fold greater seasonal deterioration observed in ICFs reflects this compounded impact, with

Table 6 Principal component analysis (PCA) of combined water quality data from ICF and NCF areas[a]

	Principal component analysis (rotated component matrix)			
Factor	PC_1	PC_2	PC_3	PC_4
Eigenvalue	9.959	9.285	2.103	1.990
% of variance	35.57	33.16	7.51	7.11
Cumulative %	35.57	68.73	76.24	83.35
PC weight (W_i)	0.427	0.398	0.090	0.085
Temperature	0.713	−0.158	−0.141	0.347
Turbidity	0.775	0.422	0.247	0.285
TSS	**0.826**	0.409	0.091	0.150
pH	−0.002	−0.074	**−0.855**	−0.095
DO	−0.818	−0.149	−0.176	−0.303
COD	0.803	0.538	0.072	0.032
BOD	0.808	0.523	0.093	0.011
EC	0.259	**0.917**	0.102	0.050
TDS	0.145	**0.946**	−0.008	0.018
TH	0.360	**0.914**	0.041	−0.096
Ca^{2+}	0.572	0.752	0.069	−0.207
Mg^{2+}	−0.054	**0.931**	0.002	0.006
Na^+	0.270	0.723	0.098	0.442
K^+	0.387	0.796	0.007	0.004
NO_3^-	**0.845**	0.333	0.290	−0.046
PO_4^{3-}	**0.872**	0.341	0.183	−0.175
SO_4^{2-}	0.442	0.340	0.180	0.622
HCO_3^-	0.095	0.843	−0.057	−0.402
Cl^-	0.078	**0.958**	−0.035	−0.002
Fe	0.153	−0.266	0.106	**0.753**
Mn	0.249	−0.083	**0.875**	0.064
Cu	0.036	0.701	0.460	0.332
Zn	**0.905**	0.018	0.008	−0.023
As	0.469	0.620	0.031	0.019
Pb	0.735	0.427	0.179	0.257
Cd	0.742	0.041	−0.075	0.136
Cr	**0.919**	0.003	−0.054	−0.012
Ni	**0.828**	0.232	0.161	0.255

[a] Rotation method: Varimax with Kaiser normalization. Bold with underscore values indicates the highest loading factor; bold only denotes the highest loading of each minimum dataset (MDS) within a given PC.

Table 7 Pearson correlation matrix of grouped MDS water quality parameters in ICF and NCF areas

Pearson correlations among MDSs														
	TSS	pH	EC	TDS	TH	Mg^{2+}	NO_3^-	PO_4^{3-}	Cl^-	Fe	Mn	Zn	Cr	Ni
TSS	1													
pH	−0.17	1												
EC	0.64[b]	−0.12	1											
TDS	0.55[b]	−0.05	0.98[b]	1										
TH	0.67[b]	−0.08	0.95[b]	0.93[b]	1									
Mg^{2+}	0.33	−0.11	0.84[b]	0.85[b]	0.85[b]	1								
NO_3^-	0.84[b]	−0.26	0.58[b]	0.46[a]	0.63[b]	0.28	1							
PO_4^{3-}	0.84[b]	−0.19	0.55[b]	0.46[a]	0.65[b]	0.28	0.94[b]	1						
Cl^-	0.49[a]	−0.07	0.91[b]	0.95[b]	0.91[b]	0.87[b]	0.35	0.39	1					
Fe	0.13	−0.11	−0.14	−0.19	−0.22	−0.19	0.07	−0.05	−0.23	1				
Mn	0.24	−0.59[b]	0.09	−0.06	0.06	−0.10	0.42[a]	0.31	−0.09	0.20	1			
Zn	0.71[b]	0.10	0.27	0.16	0.35	−0.02	0.82[b]	0.82[b]	0.07	0.24	0.28	1		
Cr	0.72[b]	0.06	0.24	0.14	0.33	−0.05	0.75[b]	0.81[b]	0.05	0.10	0.19	0.80[b]	1	
Ni	0.82[b]	−0.18	0.42[a]	0.29	0.49[a]	0.20	0.73[b]	0.74[b]	0.27	0.22	0.38	0.67[b]	0.75[b]	1

[a] Correlation is significant at the 0.05 level (2-tailed). [b] Correlation is significant at the 0.01 level (2-tailed).

effluents enriched in HMs, organic matter, and nutrients acting as the primary drivers of ecosystem health degradation. A low Water Health Index (WHI) value indicates ecological impairment characterized by habitat degradation, trophic imbalance, and reduced biological integrity. Such conditions adversely affect aquatic organisms by disrupting reproductive success, altering species composition, and increasing vulnerability to environmental stressors, ultimately compromising overall ecosystem resilience.[20,58]

3.6. Impact of cigarette-manufacturing effluents on the adjacent aquatic ecosystem toxicity

Fig. 3 presents a comparative assessment of ecological toxicity, expressed as the Maximum Ecological Risk of Metal Quotient (MERMQ), in aquatic ecosystems adjacent to ICFs and NCFs during the BCS and ACS. A marked increase in ecological toxicity was observed during ACS at both sites, reflecting the influence of agricultural runoff, with an additional contribution from industrial effluents in ICFs. In ICFs, the MERMQ increased sharply from 6.27 (BCS) to 12.21 (ACS), representing a 94.67% rise, whereas in NCFs it increased from 6.25 to 9.55, corresponding to a 52.77% rise. Thus, the seasonal increase in ecological toxicity in ICFs was approximately 1.8 times higher than in NCFs, clearly indicating the added impact of cigarette-manufacturing effluents.

Despite these differences, the MERMQ values at both sites consistently fell within the 'very high toxicity' category. Pb, Cu, and Cd were the dominant contributors to these risks; Ni exerted a moderate influence, while Cr, Zn, and As posed relatively minor risks. These patterns are consistent with those in previous studies reporting elevated HM contamination in aquatic ecosystems near industrial areas.[62] Tokatli *et al.*[37]

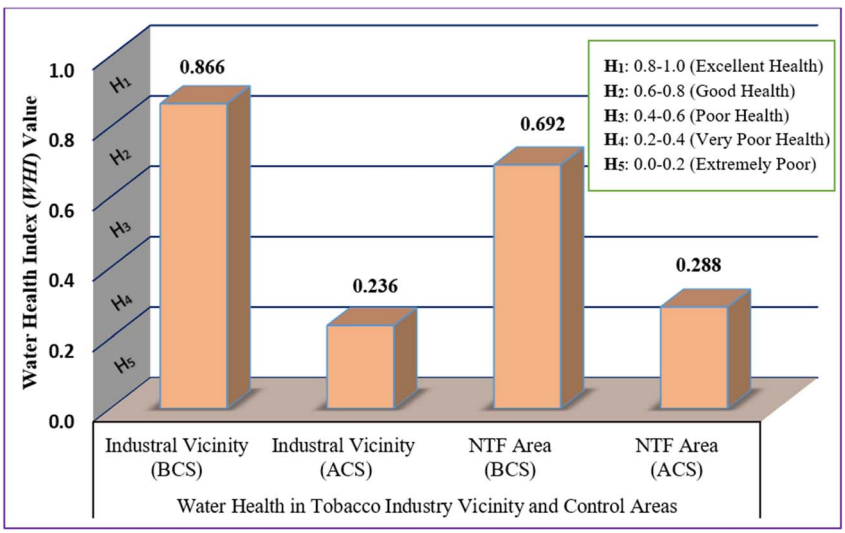

Fig. 2 Comparative status of aquatic ecosystem health between ICF and NCF waters.

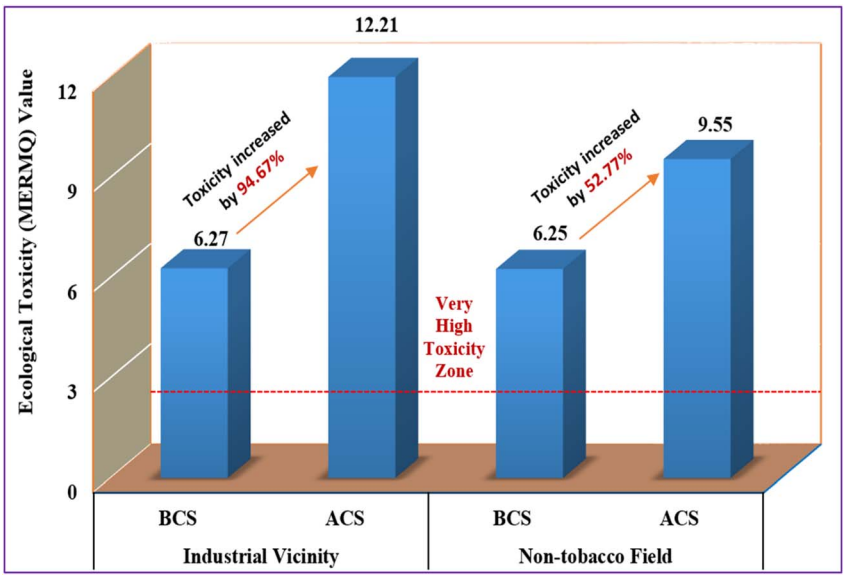

Fig. 3 Comparative assessment of ecological toxicity between ICF and NCF waters.

similarly reported elevated ecotoxicity levels in the Black Sea region, findings that are consistent with and supportive of the results of the present study. The substantially higher toxicity observed in ICFs underscores the heightened vulnerability of aquatic systems to combined industrial discharges and agricultural inputs, including fertilizers and pesticides.[42] High ecotoxicity values indicate the presence of hazardous contaminants or HMs at concentrations capable of inducing acute and chronic toxicity in aquatic biota. Prolonged exposure to such conditions can result in bioaccumulation, physiological dysfunction, impaired reproduction, and increased mortality, ultimately destabilizing trophic dynamics and reducing ecosystem resilience.[57] Overall, the results demonstrate that industry-adjacent crop fields intensify ecological toxicity more severely than non-tobacco fields, highlighting the need for rigorous effluent management and the adoption of sustainable agricultural practices to mitigate ecological toxicity and protect aquatic ecosystem integrity.

3.7. Ecological risk implications of cigarette-manufacturing effluents in nearby aquatic ecosystems

The aquatic potential ecological Risk Index (RI) was evaluated for ecosystems adjacent to cigarette-manufacturing areas and compared with that in NCF sites during both the BCS and ACS to assess the ecological risk factor (E_r^i) and overall potential ecological risk (RI). The results (Fig. 4) indicate that during BCS, the RI values were relatively comparable between the industry-adjacent crop fields (ICFs) and NCFs, with values of 359.80 and 366.89, respectively. Both sites were positioned near the threshold of the 'considerable risk' category, suggesting a similar ecological risk status during the pre-cropping period. This similarity can be attributed to the prevailing hydrological conditions during the BCS, when extensive seasonal inundation likely promoted dilution and dispersion of contaminants across the aquatic environment, thereby reducing spatial differences in pollutant concentrations between the two ecosystems. However, a pronounced intensification of ecological risk was observed during ACS. The RI value increased markedly to 690.10 in ICFs, placing it in the 'very high risk' category, whereas in NCFs the RI rose to 536.22, remaining within the 'considerable risk' category. Compared with BCS conditions, this represents an increase of 91.80% in ICFs and 46.15% in NCFs. The RI value in the industry-adjacent ecosystem was therefore approximately 1.95 times higher than that in the non-tobacco ecosystem, indicating a substantial additional pollution burden associated with cigarette-manufacturing effluents. Such seasonal escalation of ecological risk in industrially influenced aquatic systems has been widely reported and is generally attributed to increased pollutant discharge, reduced dilution capacity, and intensified agricultural runoff during the cropping season.

Analysis of the individual heavy-metal contributions revealed that the hierarchical order of ecological risk followed Cd > Pb > Cu > Ni > Cr > Zn > As, with Cd, Pb, and Cu emerging as the dominant contributors to the overall RI. Among these, Cd represented the most critical risk factor. During BCS, Cd already posed moderate to strong ecological risk, with values of 181.52 in NCFs and 172.22 in ICFs. During ACS, Cd-related risk increased substantially, rising by 36.19% in NCFs and 87.10% in ICFs, reaching strong ecological risk levels of 247.22 and 322.22, respectively. A similar but more pronounced site-specific trend was observed for Pb. In NCFs, Pb-related ecological risk increased by 98.08%, rising from 80.10 (low risk) to 158.67 (moderate risk). In contrast, in ICFs, the Pb-related risk increased dramatically by 207.08%, escalating from 75.33 (low risk) to 231.33 (strong risk). These results indicate that Pb accumulation was considerably more severe in the industrially influenced ecosystem, highlighting the likely contribution of cigarette-manufacturing discharges to heavy-metal enrichment. In comparison, Cu contributed more moderately to the overall

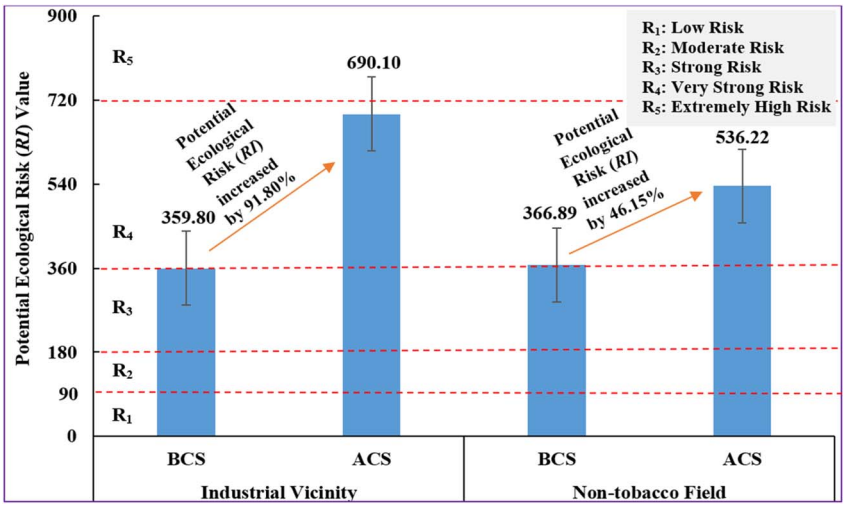

Fig. 4 Comparative evaluation of potential ecological risks (RI) between ICF and NCF waters.

ecological risk. The ecological risk values for Cu increased from 93.81 to 110.11 in NCFs (17.37% increase) and from 100.54 to 114.25 in ICFs (13.64% increase), remaining within the 'moderate ecological risk' category at both sites. Although several HMs contributed to the overall RI, the disproportionately higher increases in Cd and Pb within the industry-adjacent ecosystem clearly indicate that cigarette-manufacturing effluents play a critical role in intensifying ecological risks in nearby aquatic environments. From an ecological perspective, elevated RI values reflect substantial contamination by toxic elements capable of exerting severe stress on aquatic organisms. Chronic exposure to such contaminants can result in bioaccumulation within biological tissues, disruption of enzymatic and metabolic processes, impaired reproductive performance, and increased mortality rates. These physiological stresses may ultimately alter community composition, reduce biodiversity, and compromise the long-term stability and resilience of aquatic ecosystems.[57] Collectively, these findings emphasize the urgent need for effective industrial wastewater treatment, continuous monitoring of priority heavy metals, particularly Cd, Pb, and Cu, and strict enforcement of environmental regulations to mitigate the ecological risks associated with effluent discharges from cigarette-manufacturing industries.

3.8. Impact of cigarette effluents on the surrounding aquatic ecosystem: health hazard risks

Cigarette-manufacturing effluents represent a significant source of chemical stressors to adjacent aquatic ecosystems, thereby exacerbating ecological degradation and increasing health hazard risks for aquatic organisms. These risks are particularly pronounced in ICF waters, where industrial discharges act synergistically with agricultural runoff, compared with NCF waters that are predominantly influenced by agricultural inputs alone. Fig. 5 presents box plots of the Hazard Quotient (HQ) and Hazard Index (HI) values for nine studied HMs, with the threshold value of 1 indicated by a red dashed line. During the baseline cropping season (BCS), the HQ values for Cd, Cr, Ni, As, and Fe substantially exceeded the threshold level in both ICF and NCF waters, whereas Mn, Cu, Zn, and Pb remained below the threshold. Despite differences in pollution sources, a broadly similar HQ distribution pattern was observed between the two field types during the BCS. This similarity is mainly attributable to the pre-BCS period, during which extensive land submergence led to hydrological mixing, resulting in comparable water quality parameters and, consequently, similar HQ risk intensities across the study sites. In contrast, during the ACS, HQ values for all studied HMs increased markedly and exceeded the threshold level in both fields. Notably elevated HQ values were recorded for Cd (ICF: 10.74; NCF: 8.24), Cr (ICF: 3.36; NCF: 2.88), Ni (ICF: 4.07; NCF: 3.82), As (ICF: 1.97; NCF: 2.01), and Fe (ICF: 1.59; NCF: 1.58), while Pb also exceeded the threshold in both ICF (1.88) and NCF (1.29) waters during the ACS. The relative increase in HQ values from BCS to ACS followed the order: Pb (207.08%) > Zn (157.48%) > Ni (96.07%) > Cd (87.10%) > As (71.01%) > Cr (54.16%) > Mn (37.54%) > Fe (28.69%) > Cu (13.64%) in ICF waters, and Pb (98.08%) > As (91.27%) > Ni (87.06%) > Cd (36.19%) > Cr (35.27%) > Zn (27.72%) > Fe (22.05%) > Cu (17.37%) > Mn (10.91%) in NCF waters (Fig. 5). Based on the Hazard Index (HI), both ICF and NCF waters exhibited values exceeding the 'high-risk zone' during the BCS (ICF: 14.82; NCF: 14.96), indicating comparable cumulative hazard levels at this stage. Following the cropping season, the HI values increased sharply in both systems, rising by 77.64% in ICF and 46.17% in NCF waters and reaching 26.33 and 21.87, respectively, well above the high-risk threshold. Consequently, the cumulative hazard risk to aquatic life in ICF waters was approximately 1.67 times higher than that in NCF waters. These elevated HQ and HI values are consistent with findings reported by Hossen and Mostafa[25] in aquatic environments adjacent to personal care product industries in Bangladesh and Tokatli *et al.*[37] in Black Sea region of Türkiye, further supporting the robustness and regional relevance of the present results.

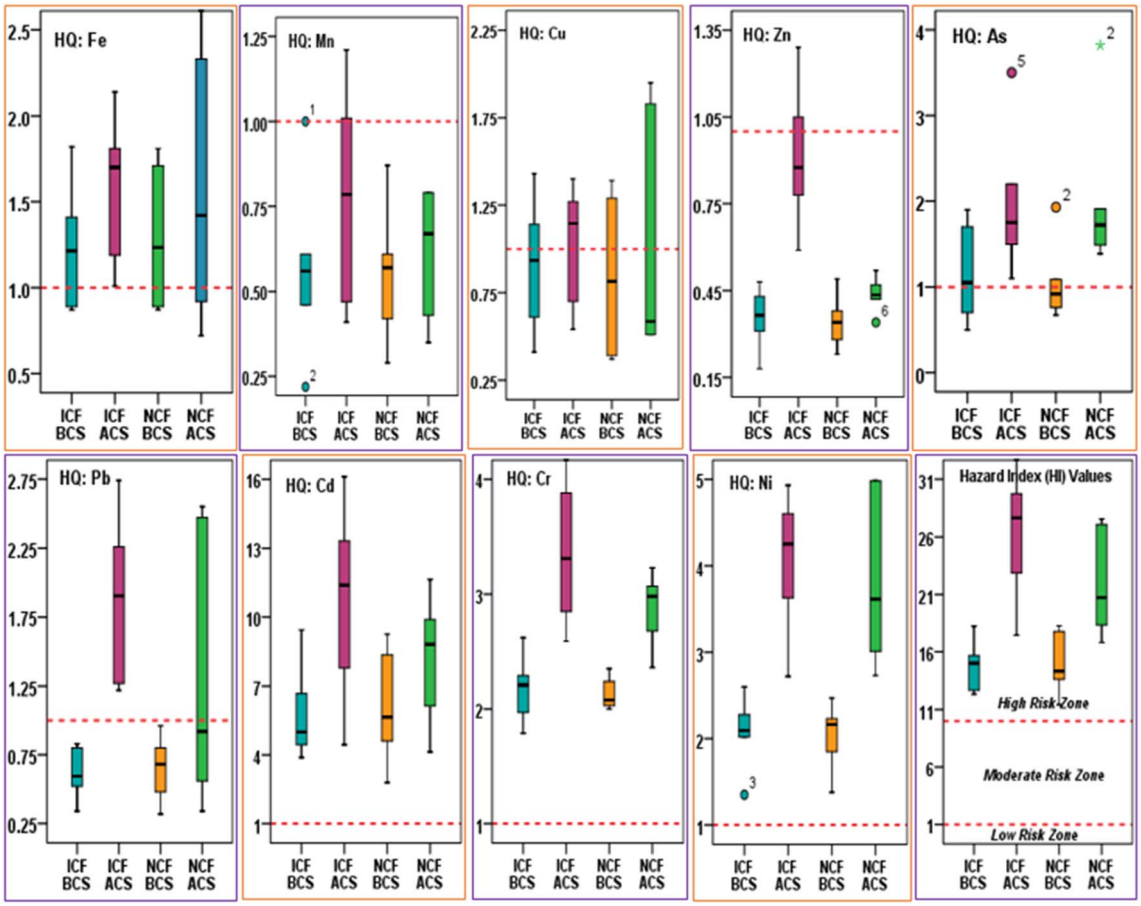

Fig. 5 Box plots illustrating the distribution of Hazard Quotient (HQ) and Hazard Index (HI) values in the studied water samples.

The background geochemical characteristics of the study area (AEZ-11) play an important role in shaping metal dynamics in the surrounding aquatic ecosystems. Previous studies have reported that soils in this region are naturally enriched in Fe, with significant to very high enrichment of As, Cd, and Ni, moderate enrichment of Pb and Cr, and predominantly geogenic origins for Fe, Mn, Zn, and Cu.[41,47,63] These inherent soil properties provide a baseline against which the influence of cigarette-manufacturing effluents on surface water quality can be interpreted. In surface waters, Fe concentrations increased comparably in both industrial-adjacent crop fields (ICFs: 28.69%) and non-tobacco crop fields (NCFs: 22.05%), indicating a dominant contribution from soil–water interactions rather than industrial discharges. Similarly, Mn and Cu exhibited only minor increases in both field types, and their concentrations in tobacco effluents were relatively low. Consequently, these elements pose limited ecological hazards to aquatic organisms and are most plausibly derived from natural soil sources rather than cigarette-manufacturing activities. In contrast, Zn displayed a markedly higher increase in ICF waters compared with NCF waters, consistent with its elevated concentration in tobacco effluents. This pattern suggests a substantial industrial contribution, likely originating from tobacco leaf processing. Tobacco plants are known to exhibit strong (>1) Zn bioaccumulation and translocation capacity, which facilitates the transfer of Zn into processing wastes and subsequently into receiving waters.[41,64] Arsenic (As) presented a different behavior. Although As concentrations in tobacco effluents were relatively low (0.014 mg L^{-1}), its hazard risk increased similarly in both ICF (71.01%) and NCF (91.27%) waters. This indicates that agricultural inputs, particularly phosphate fertilizers such as DAP and pesticide applications, are the primary sources of As enrichment in surface waters rather than industrial effluents.[65,66] Conversely, Cd, Ni, Pb, and Cr exhibited very high increases in hazard risks across both field types, accompanied by elevated concentrations in cigarette-manufacturing effluents. These findings imply a combined contribution from industrial discharges and agricultural inputs. Tobacco effluents can introduce these metals through multiple pathways, including the processing of metal-accumulating tobacco leaves, mechanical abrasion during manufacturing, and the extensive use of industrial chemicals. The tobacco manufacturing sector employs thousands of chemical compounds, including those used in processes such as Dry Ice Expanded Tobacco (DIET), while finished cigarettes themselves contain more than 7000 chemical constituents.[67] Together, these factors substantially amplify the metal burden in adjacent aquatic systems. Overall, this assessment indicates that Cd, Ni, Cr, and Pb represent the

highest-priority contaminants associated with cigarette-manufacturing effluents, with additional concern for As and Zn due to their cumulative agricultural and industrial inputs. Elevated hazard quotient (HQ) and hazard index (HI) values in aquatic ecosystems indicate substantial non-carcinogenic risks to resident biota, reflecting sustained exposure to toxic contaminants at concentrations exceeding ecological safety thresholds. Persistently high HQ and HI levels can impair physiological functions, disrupt reproductive success, and reduce population resilience, ultimately compromising ecosystem stability and trophic integrity.[37,57] Effective treatment of tobacco effluents prior to discharge or reuse is therefore essential to reduce health hazard risks to aquatic organisms, protect aquatic biota, and ensure the long-term sustainability of surrounding aquatic ecosystems.

Extensive research has demonstrated the effectiveness of a range of advanced technologies for treating industrial effluents, including coagulation, adsorption, and coagulation–adsorption hybrid systems, biodegradation, electrochemical degradation, ozonation, chemical oxidation and precipitation, ion exchange, membrane filtration, and advanced oxidation processes.[32,61] The successful application of these technologies depends on accurate identification of specific pollutant profiles, which enables targeted and efficient contaminant removal.[68] When appropriately implemented, such treatment strategies can reduce pollutant concentrations to environmentally safe levels, allowing wastewater discharge without compromising aquatic ecosystem integrity. Furthermore, treated effluents that retain essential nutrients may be safely reused for irrigation, supporting sustainable crop production while reducing pressure on freshwater resources. In the case of cigarette-manufacturing effluents, elevated hazards are primarily associated with high concentrations of Cd, Ni, Cr, and Pb, along with excessive physicochemical loads, including turbidity, TSS, TH, COD, BOD_5, PO_4–P, NO_3–N, and HCO_3^-, coupled with depleted DO. These characteristics necessitate integrated treatment approaches targeting both HMs and key physicochemical contaminants. The present study provides critical insights into priority pollutants driving water quality degradation and ecological risks in adjacent aquatic systems, with direct relevance to multiple United Nations Sustainable Development Goals (SDGs). The findings most strongly support SDG 6 (clean water and sanitation), SDG 12 (responsible consumption and production), and SDG 14 (life below water), with additional contributions to SDG 15 (life on land) and SDG 3 (good health and well-being). Collectively, these linkages highlight the study's significance for global sustainability agendas by advancing pollution control, aquatic ecosystem protection, and sustainable industrial wastewater management. Nonetheless, certain limitations remain, indicating the need for further targeted research. Biological indicators, particularly macro-invertebrates, fish, phytoplankton, and macro-phytes, offer robust and complementary tools for evaluating aquatic ecosystem health. The application of widely accepted biological indices, including the Biological Monitoring Working Party (BMWP) score, Average Score per Taxon (ASPT), Fish Index of Biotic Integrity (F-IBI), Trophic State Index (TSI) based on phytoplankton response, and so on, enables sensitive detection of ecological degradation. When integrated with physicochemical and ecotoxicological indices, these tools substantially enhance the reliability of ecological risk assessments, particularly in industrially influenced waters receiving cigarette-manufacturing effluents.

4 Conclusion

This study provides compelling evidence that cigarette-manufacturing effluents substantially intensify chemical loading, ecological stress, and non-carcinogenic hazard risks in adjacent aquatic ecosystems. Although baseline conditions during the BCS were comparable between ICFs and NCFs, pronounced seasonal deterioration occurred during the ACS, when several physicochemical parameters and heavy metals exceeded AEQ thresholds. The magnitude of degradation was consistently and statistically greater in ICF waters, where key indicators, including turbidity (94.61 ± 28.21 NTU), TSS (132.67 ± 24.40 mg L^{-1}), DO (3.19 ± 0.63 mg L^{-1}), COD (269 ± 79.88 mg L^{-1}), BOD_5 (153 ± 59.33 mg L^{-1}), nutrients such as NO_3–N (18.87 ± 4.87 mg L^{-1}) and PO_4–P (3.21 ± 1.12 mg L^{-1}), and trace metals including Zn (0.071 ± 0.023 mg L^{-1}), Pb (0.116 ± 0.038 mg L^{-1}), Cd (0.019 ± 0.007 mg L^{-1}), Cr (0.114 ± 0.023 mg L^{-1}), and Ni (0.175 ± 0.034 mg L^{-1}), approached nearly double the concentrations observed in NCF systems. These patterns demonstrate the additive and synergistic influence of industrial discharges together with agricultural runoff. Irrigation water suitability indices (SSP, SAR, RSBC, KR, and MH) showed significant seasonal variation from BCS to ACS in both fields, largely reflecting agricultural runoff with only limited influence from tobacco-industry effluents. In contrast, the chloro-alkaline indices (CAI-1 and CAI-2) displayed relatively minor and statistically non-significant variation among sampling groups, indicating weak ion-exchange processes between water and surrounding geological materials. Water quality index (WQI) and water health index (WHI) assessments further revealed a marked seasonal decline, with overall deterioration reaching up to 321.36% during ACS. Water quality for both irrigation suitability and aquatic ecosystem health shifted from 'good' to 'extremely poor' categories, with degradation intensities approximately 1.56–2.54 times higher in ICF waters than in NCF waters. This decline was primarily driven by turbidity, TSS, BOD_5, DO, PO_4–P, NO_3–N, and K^+. Toxicity and ecological risk indicators also demonstrated substantially greater stress in the industry-adjacent ecosystem. The mean effect range-median quotient (MERMQ) increased by 94.67% in ICFs compared with 52.77% in NCFs, indicating an approximately 1.8-fold higher seasonal toxicity increase in the industrial vicinity. Pb, Cd, and Cu were identified as the dominant contributors, while Ni exerted a moderate influence. Similarly, the potential ecological risk index (RI) increased to the 'very high risk' category during ACS, with RI values nearly twice as high in ICFs compared with NCFs. Hazard quotient (HQ) analyses further identified Cd, Ni, Cr, and Pb as priority contaminants, with cumulative hazard index values indicating

ecological risks to aquatic organisms approximately 1.7 times higher in ICF waters. Collectively, these findings demonstrate substantial contamination of industry-adjacent aquatic ecosystems relative to NCF systems, resulting in pronounced deterioration of water quality and ecosystem health, increased toxicity, and elevated hazard risks to aquatic organisms. Effective wastewater treatment prior to discharge could significantly reduce these impacts while enabling the safe reuse of nutrient-rich effluents for irrigation, thereby protecting adjacent aquatic ecosystems and supporting progress toward multiple SDGs. Future research should integrate high-resolution temporal monitoring, metal speciation and bioavailability assessments, biomarker-based ecotoxicological responses, and ecosystem-level modeling approaches to improve causal attribution and strengthen predictive risk frameworks for industrially impacted aquatic environments.

Consent for publication

All authors consent to the publication of this manuscript.

Author contributions

Anupam Roy: conceptualization, methodology, investigation, formal analysis, data curation, visualization, writing – original draft, writing – review & editing. M. G. Mostafa: conceptualization, methodology, supervision, writing – review & editing, project administration.

Conflicts of interest

The authors declare no potential conflict of interest.

Data availability

Additional data are available from the corresponding author upon request.

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