



MICROPLASTIC POLLUTION IN FRESHWATER ECOSYSTEMS: SOURCE APPORTIONMENT, SPATIAL HETEROGENEITY, AND INTEGRATED ECOLOGICAL RISK ASSESSMENT

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ABSTRACT

Microplastic pollution has emerged as a significant environmental issue in freshwater environments due to uneven extent, origin, and effects of the pollution on space and seasons. This research considered microplastic pollution using a comprehensive framework of spatial heterogeneity, source contributions, environmental relationships, and ecological risk. Five hundred freshwater observations, including upstream, midstream, and downstream sections in four seasons and four land-use categories were used to determine the quantitative environmental evaluation. The abundance of microplastic, contamination of sediment, physicochemical parameters, source contributions, Pollution Load Index, Polymer Hazard Score, and Integrated Ecological Risk Index were examined using descriptive statistics, chi-square tests, correlation, and regression. The lowest ecological risk and highest freshwater and sediment microplastic contamination were found in downstream reaches. The intensity of pollution was usually higher in monsoon conditions, but season was not found to be a significant factor in ecological-risk classification. River reach and land use had a significant risk association. The abundance of microplastic was positively related to sediment contamination, conductivity, turbidity, wastewater, industrial contribution, polymer hazard, and ecological risk, and negatively related to dissolved oxygen. The regression analysis revealed that a number of environmental and anthropogenic factors are important predictors. Spatial setting, land use, source characteristics, and the local environmental conditions had a strong influence on the cause of Freshwater microplastic pollution. There is a need to have integrated surveillance and source-control measures especially in downstream, urban and industrial regions.

Keyword: Microplastics; Freshwater ecosystems; Source apportionment; Spatial heterogeneity; Ecological risk

Introduction

Microplastic contamination is a significant issue in freshwater ecology due to the growing evidence of these recalcitrant particles in rivers, lakes, and reservoirs, streams, and sediments. Freshwater systems serve to be sinks as well as transport systems that carry land-based plastic debris to the downstream and marine systems. Their tenacity, motility, and contact with aquatic organisms has elicited the concern of long-term ecological impacts (Bae et al., 2025). Basin-level evaluations have also shown that there is a significant spatial distribution in the prevalence and ecological hazard of microplastic (Huang et al., 2023). Freshwater microplastics have a variety of anthropogenic sources, such as wastewater discharge, urban runoff, agricultural activities, industrial activities, fishing, tourism, and recreational usage. Microplastics can be carried by both local and long-range transport routes (even to relatively remote freshwater settings) (Feng et al., 2024). To this end, source-apportionment methods have become more and more popular in distinguishing pollution indicators related to particular human actions (He et al., 2026), and flux-based models are employed to estimate the quantitative contribution of sources to river systems (Li, B., et al., 2026).

Contamination of microplastics is often not evenly distributed in freshwater. Due to the general higher pressure of anthropogenic actions in downstream regions, upstream areas are not as susceptible to such effects, with the midstream and downstream region likely to receive particles due to settlements, industries, tributaries, and waste water inflows. Spatial heterogeneity is as such brought about by land use, population density, hydrodynamics, sedimentation, and channel characteristics. The multidimensional characteristics of particles can assist in tracking the sources and the source-related ecological risks (Li, S., et al., 2025). Other spatial techniques have found a clear-cut pattern of contaminants in river and lake systems (Ge et al., 2025; Li, X., et al., 2026). Microplastic transport, dilution, deposition and resuspension are also influenced by seasonal hydrology. Monsoonal rainfall can enhance the terrestrial runoff and downstream transportation, and periods of low flow can foster local accumulation. Physicochemical variables may also affect distribution including turbidity, conductivity, dissolved oxygen, pH, and temperature. The hydrological seasonality has been reported to alter the land-use impacts on the riverine microplastic pollution (Chen et al., 2026), and the hydrodynamic conditions may alter the particle fate and source-specific hazard (Sivodia et al., 2026).

To efficiently manage pollution, it is necessary to identify dominant sources. The ecological-risk interpretation of the aquatic environment has been enhanced with the help of source-apportionment frameworks that combine spatial patterns and contaminant properties (Duan et al., 2026). Other components of multi-source systems such as stream sediments have been studied using similar methods to detect anthropogenic inputs and rank environmental risks (Junior et al., 2026; Mengu Junior et al., 2026; Shi et al., 2026). Ecological evaluation is also essential since the abundance of microplastic does not indicate the overall environmental risk. Ecological effects can be modified by polymer composition, persistence, particle properties and the toxicity associated with it. Combinative methods that involve pollution loading

and polymer-specific hazard are better at offering a more comprehensive evaluation of freshwater risk (Lu et al., 2026). There are also ecological risks that are polymer-driven and source-specific exposure routes that are highlighted in more comprehensive freshwater evaluations (Mohan & Lakshmanan, 2026).

Although there is increasing research, there is limited research that portrays a combination of source apportionment, spatial heterogeneity, seasonal variability, environmental properties and ecological risk in a single study. Integrated spatial strategies have been shown to be of high value to interpret risk of contaminants in complex waters (Gopinath et al., 2026), and microplastic research has indicated the utility of combining distribution analysis with sources and ecological risk (Liu et al., 2023). As such, this work evaluated spatial and seasonal distribution of microplastic, determined key source sources and environmental associations and measured freshwater contamination using an ecological-risk nexus.

Objectives of the study

1. To assess spatial and seasonal variation in freshwater microplastic pollution and ecological risk.
2. To identify environmental and anthropogenic predictors of freshwater microplastic abundance.

2. Methodology

2.1 Study Design

The quantitative cross-sectional design of environmental assessment was employed to determine microplastic contamination, spatial variability, and source inputs and ecological risk in freshwater. The research sample consisted of 500 observations that were spread in various freshwater sampling sites. The sampling design was a description of upstream, midstream, and downstream river reaches and four seasons. All observations included physicochemical water data, freshwater and sediment microplastic, pollution-source, polymer-related hazard data, and composite ecological-risk data.

2.2 Spatial and Seasonal Sampling

Sampling sites were stratified into upstream, midstream and downstream to check the spatial variation along the freshwater system. Sites were also divided based on the type of surrounding land use where most of the surrounding was either forest/rural, agricultural, mixed, urban, and industrial. Seasonal cover consisted of pre-monsoon, monsoon, post-monsoon and winter. Repeated measurements were ensured between spatial and seasonal classes to allow to compare the degree of pollution, sediment contamination, source effects, and ecological-risk dynamics under varying hydrological and anthropogenic environmental settings.

2.3 Environmental and Microplastic Variables

The physicochemical water parameters were temperature, pH, dissolved oxygen, electrical conductivity, and turbidity. The abundance of freshwater microplastic was in items per litre, and sediment contamination in items per kilogram. The indicators related to pollution were Pollution Load Index, Polymer Hazard Score, and Integrated Ecological Risk Index. Variables of source-apportionment were proportional contribution of

wastewater, urban runoff, agricultural activities, industrial activities and fishing/tourism. These variables were employed to describe the patterns of contamination and assess the environmental factors related to the abundance of microplastics.

2.4 Spatial and Seasonal Pollution Assessment

Spatial heterogeneity was measured by comparing the abundance of microplastic, microplastic concentrations of the sediment, and the integrated ecological-risk values of the upstream, midstream, and downstream reaches. The seasonal variation was also analyzed in pre-monsoon, monsoon, post-monsoon and winter seasons. The continuous pollution indicators were summarized with mean and standard deviation of each spatial and seasonal group. This method of analysis has allowed identifying sites and seasons with a relatively high contamination level and a systematic framework to explain the distribution of freshwater microplastic pollution and ecological risk.

2.5 Ecological Risk Assessment

The Integrated Ecological Risk Index, the Pollution Load Index and Polymer Hazard Score were used to assess ecological risk. The composite index indicated the changes in the intensity of microplastic pollution and the property of the hazards of polymers. The index thresholds were used to determine the low, moderate, high and very high ecological-risk categories into which samples were classified. Each category was calculated to give frequencies and percentages. The comparison of risk classifications was also done across river reaches, land-use categories and seasons to ascertain whether the ecological-risk distribution was different by spatial and environmental conditions.

2.6 Statistical Analysis

The statistical analysis was done using descriptive and inferential techniques. The frequencies and percentages were used to summarize categorical variables, but the mean and standard deviation were used to summarize continuous variables. Pearson chi-square test was employed to determine relationships between ecological-risk categories and river reach, land use, and season. Correlation analysis was used to investigate the association of abundance of microplastic with environmental, source-related and ecological-risk variables. Regression was used to determine independent predictors of the abundance of microplastic. A p-value of 0.05 was taken as significant.

3. Results

3.1 Distribution of Sampling Characteristics and Ecological Risk

This analysis involved 500 freshwater observations that were spread out in upstream, midstream and downstream reaches. The proportion of midstream sites was 36.0%, downstream and upstream 32.0 each. Every season made its equal contribution, as there were 125 observations. Ecological-risk classification revealed that very high risk was found in 47.8 percent of samples, then low risk 19.0 percent, moderate risk 17.6 percent and lastly, high risk 15.6 percent. The overall distribution is presented in Table 1.

Table 1. Frequency and percentage distribution of sampling characteristics and ecological-risk categories (N = 500)

Characteristic	Category	Frequency (n)	Percentage (%)
River reach	Upstream	160	32.0
	Midstream	180	36.0
	Downstream	160	32.0
Dominant land use	Forest/Rural	100	20.0
	Agricultural	100	20.0
	Mixed	100	20.0
	Urban	100	20.0
	Industrial	100	20.0

The sampling seasons and ecological risk types were spread across the freshwater observations as is shown in Figure 1.

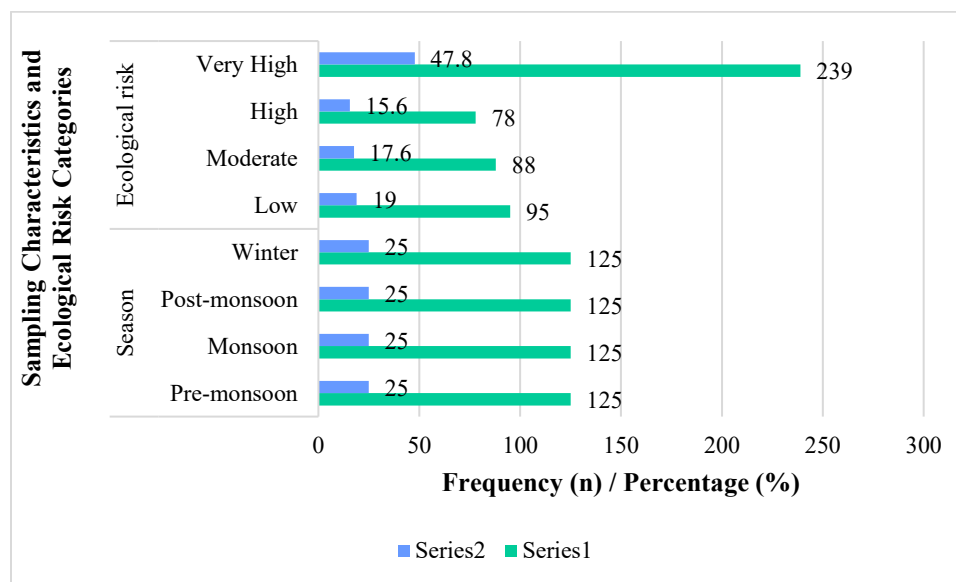


Figure 1. Sampling Distribution and Ecological Risk Categories

Figure 1 indicates the balanced seasonal sampling design with an apparent concentration of observations in the higher ecological risk categories. The trend shows that the temporal coverage was well balanced, and ecological risk was not evenly distributed, implying that the conditions related to pollution were significantly different throughout the freshwater sampling framework and the places where the study was conducted on the whole.

3.2 Microplastic Pollution and Environmental Characteristics

The average abundance of freshwater microplastic was 201.39 ± 165.75 items/L and the average abundance of sediment contamination was 2928.18 ± 2495.95 particles/kg. The average Pollution Load Index was 2.01 ± 1.66 , and the Polymer Hazard Score was 11.18 ± 3.86 . The Integrated Ecological Risk Index was quite variable, with mean equal to 266.72 with standard deviation of 299.86. The dissolved oxygen, electrical conductivity, and turbidity were found to be 6.70 ± 1.52 mg/L, 414.55 ± 183.57 μ S/cm, and 26.17 ± 15.31 NTU respectively.

Figure 2 shows the general location of indicators of microplastic pollution and the environmental parameters.

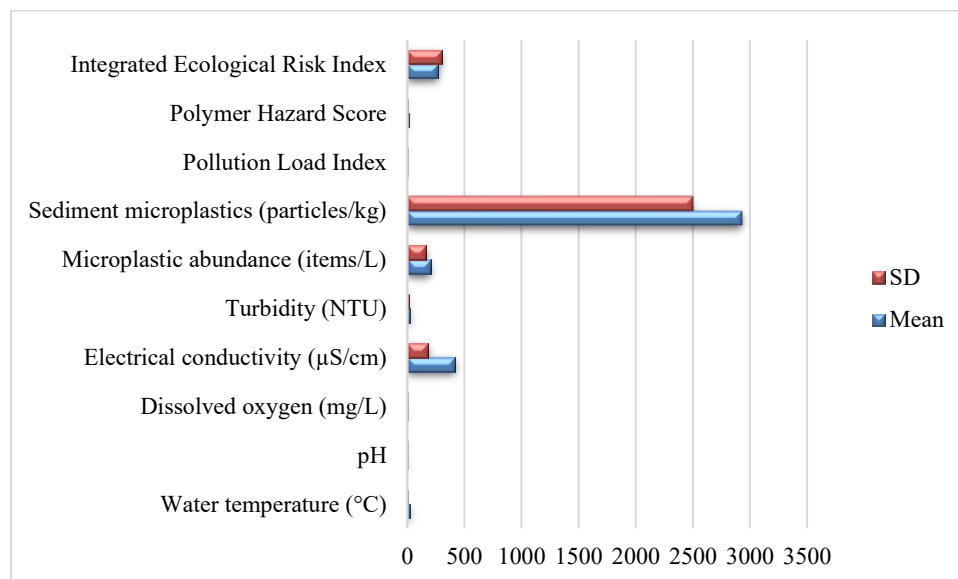


Figure 2. Pollution and Environmental Parameters

Figure 2 points out that there is a significant difference between the pollution indicators and environmental features of the fresh water samples. The highest total magnitude was exhibited by the contamination of sediments, and reasonable variations were also observed in water-column abundance and ecological risk. The physicochemical parameters were relatively constant, which implies the opposite scales between the environmental conditions and measurements of pollution related to microplastic.

3.3 Spatial and Seasonal Heterogeneity of Microplastic Pollution

A distinct spatial gradient was also evident where downstream sites had the highest amount of freshwater microplastics (392.97 ± 121.37 items/L) followed by the midstream sites (170.29 ± 85.29 items/L) and the upstream sites (44.79 ± 24.25 items/L). The trend was the same in case of sediment contamination and ecological risk. The abundance of microplastics and risk to the ecology were greatest in the monsoon and lowest in winter seasons. On the whole, the spatial and seasonal variations differed significantly, as shown in Table 2.

Table 2. Spatial and seasonal variation in freshwater microplastic contamination

Group	Microplastic abundance (items/L), Mean $\pm$ SD	Sediment microplastics (particles/kg), Mean $\pm$ SD	Integrated ecological risk, Mean $\pm$ SD
River reach			
Upstream	44.79 $\pm$ 24.25	675.05 $\pm$ 423.21	39.80 $\pm$ 17.66
Midstream	170.29 $\pm$ 85.29	2454.20 $\pm$ 1372.69	161.25 $\pm$ 87.46
Downstream	392.97 $\pm$ 121.37	5714.55 $\pm$ 2018.78	612.29 $\pm$ 297.82

Figure 3 shows the seasonal changes of microplastic abundance, sediment contamination, and ecological risk indicators.

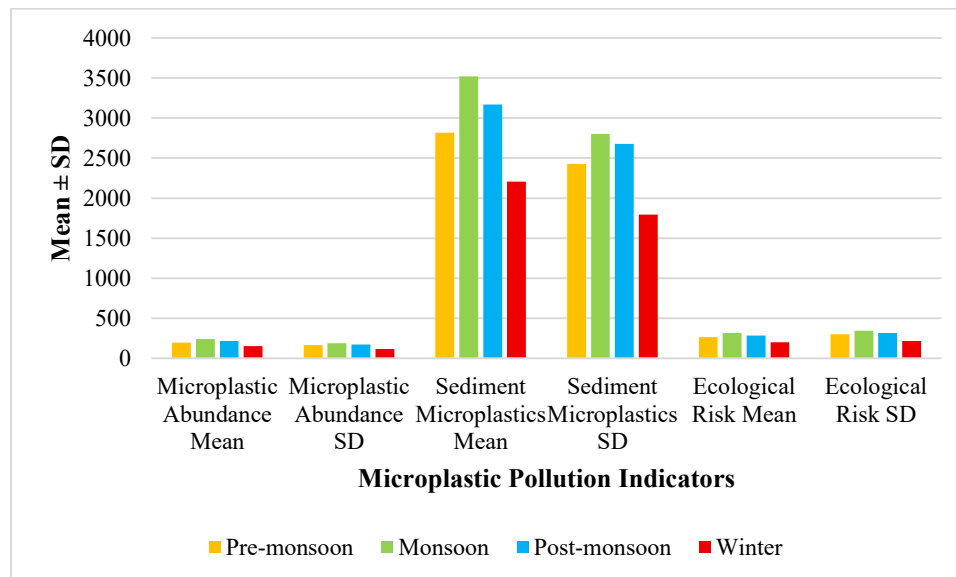


Figure 3. Seasonal Variation in Microplastic Pollution

Figure 3 shows that there are distinct seasonal variations in the key indicators of microplastic pollution. Monsoon conditions were mostly characterized by higher levels of pollution, then post-monsoon and pre-monsoon seasons, and winter was characterized by rather lower levels. The trend indicates that seasonal hydrology could affect the movement of microplastics, their accumulation, sedimentation, and the risk to the ecology.

3.4 Association of Spatial and Environmental Factors with Ecological Risk

Chi-square analysis found significant results that exist between ecological-risk classification and river reach and dominant land use. River reach was strongly associated with ecological risk ($\chi^2 = 548.22$, $df = 6$, $p < 0.001$), while land use showed an even stronger association ($\chi^2 = 846.50$, $df = 12$, $p < 0.001$). Conversely,

ecological-risk classification did not differ significantly with seasonal variation ($\chi^2 = 11.65$, $df = 9$, $p = 0.234$), as shown in Table 3.

Table 3. Chi-square analysis of factors associated with ecological-risk classification

Factor	χ^2	df	p-value	Interpretation
River reach	548.22	6	<0.001	Significant
Dominant land use	846.50	12	<0.001	Significant
Season	11.65	9	0.234	Not significant

3.5 Correlation of Microplastic Abundance with Environmental and Source Variables

Correlation analysis indicated that there was a very strong, positive relationship between the freshwater and sediment microplastic contamination ($r = 0.955$, $p < 0.001$). The abundance of microplastic was positively related to electrical conductivity, turbidity, wastewater contribution, urban runoff, industrial contribution, Polymer Hazard Score and Integrated Ecological Risk Index. There was a strong negative correlation between dissolved oxygen ($r = -0.912$, $p < 0.001$). The agricultural and fishing/tourism contributions were also found to be negatively correlated to abundance. The entire correlation findings are in Table 4.

Table 4. Correlations between freshwater microplastic abundance and selected variables

Variable	Pearson r	p-value
Sediment microplastics	0.955	<0.001
Water temperature	0.116	0.009
pH	-0.089	0.046
Dissolved oxygen	-0.912	<0.001
Electrical conductivity	0.788	<0.001
Turbidity	0.695	<0.001
Wastewater contribution	0.534	<0.001
Urban runoff contribution	0.348	<0.001
Agricultural contribution	-0.605	<0.001
Industrial contribution	0.697	<0.001

Fishing/Tourism contribution	-0.617	<0.001
Polymer Hazard Score	0.651	<0.001
Integrated Ecological Risk Index	0.927	<0.001

3.6 Predictors of Freshwater Microplastic Abundance

The abundance of freshwater microplastic was significantly predicted by regression ($F = 535.87$, $p < 0.001$), which explained 90.8% of the observed variance ($R^2 = 0.908$, adjusted $R^2 = 0.906$). The strongest negative predictor was dissolved oxygen ($= -0.546$, $p = 0.001$). The variables that exhibited significant positive relationships included turbidity, industrial contribution, electrical conductivity, wastewater contribution and water temperature, and the variable that showed a significant negative relationship included agricultural contribution. After adjustment, pH and urban runoff did not significantly differ, as in Table 5.

Table 5. Regression predicting freshwater microplastic abundance

Predictor	B	SE	Standardized β	t	p-value
Constant	418.226	72.331	-	5.782	<0.001
Water temperature	1.970	0.527	0.053	3.740	<0.001
pH	1.062	8.570	0.002	0.124	0.901
Dissolved oxygen	-59.712	2.546	-0.546	-23.454	<0.001
Electrical conductivity	0.100	0.031	0.111	3.189	0.002
Turbidity	1.710	0.225	0.158	7.613	<0.001
Wastewater contribution	0.832	0.386	0.069	2.154	0.032
Urban runoff contribution	0.556	0.545	0.027	1.019	0.309
Agricultural contribution	-0.862	0.242	-0.098	-3.561	<0.001
Industrial contribution	1.492	0.466	0.145	3.203	0.001

Model summary: $R^2 = 0.908$; adjusted $R^2 = 0.906$; $F = 535.87$; $p < 0.001$.

4. Discussion

The current study showed that there was significant spatial variability in freshwater microplastic pollution, with downstream locations significantly more contaminated than midstream and upstream. Sediment microplastic concentrations and composite ecological risk had the same spatial gradient, which implied that downstream regions acted as significant accumulating zones. Seasonal variation was also observed, with

relatively higher contamination levels in monsoon and low in winter, however season was not significantly related to ecological-risk category. These results imply that spatial location, land utilization, and local man-made pressures have greater influence on the risk of microplastic than seasonal ones. The downstream enrichment observed is in line with the findings that have been obtained in the past that microplastics found in rivers accumulate in regions of urbanization, wastewater release, and a convergence of water bodies. Similar phenomena were also observed by Wang and Yu (2026): the strong spatial variability and clear source signature in an urban river system were found, and human activity impacts distribution of microplastics downstream. Similarly, the Wang et al. (2025) report found the heterogeneous presence of microplastics, a variety of sources, and inconsistent ecological hazards in a freshwater lake setting. Combined, these studies confirm the current observation that microplastic pollution is highly organised around catchment features as opposed to a uniform distribution.

Patterns related to sources also revealed that wastewater, urban runoff and industrial activities were significant sources of contamination. The industrial contribution was observed to be strongly related with microplastic abundance and the wastewater contribution also remained significant during multivariate analysis. These trends are ecologically realistic since densely populated regions are known to produce intricate plastic inputs via domestic effluents, road runoff, industrial processing, and plastic rubbish. Other aquatic contaminants have been analysed using more or less identical integrated source-apportionment systems and have proven that spatial distribution in combination with source information can better identify hotspots of pollution and management priorities (Yan et al., 2025). The environmental correlations also gave an understanding of the processes that affect the distribution of microplastics. Abundance was positively related to conductivity and turbidity but with a strong negative relationship with dissolved oxygen. High turbidity can be an indication of high suspended content and run off that can carry microplastic, but a high conductivity can be a sign of greater anthropogenic impact. The negative correlation with dissolved oxygen implies that very polluted reaches can be associated with poor water-quality parameters. Albeit on metal contaminants, Xu et al. (2026) also revealed the importance of combining environmental gradients, source attribution, and ecological risk in the interpretation of spatial contamination patterns in aquatic sediments.

The ecological-risk results support the significance of leaving the abundance of particles. Almost half of the observations were very high risk, and the allocation of risk was heavily linked with river reach and land use. This means that ecological hazard was not just influenced by the degree of contamination but also by the circumstances of the sampling environment. Wang et al. (2026) also demonstrated that integrated distribution, source-apportionment, and ecological-risk methods could differentiate the areas that should be given more attention to the environment. Biological implications are also significant since exposure to microplastic can modify aquatic community composition and organismal behavior, Yu et al. (2026) found that planktons had difference responses to microplastic pollution in a river system.

These findings can be used in practice in freshwater management. The control of pollution activities should focus on downstream, urban, and industrial areas, with special consideration on the effectiveness of wastewater treatment, stormwater management, plastic waste management, and industrial discharge control. The uniform sampling method would probably be inefficient as the risk and intensity of pollution were highly heterogeneous in space.

The research was however limited. The source contributions have been based on structured environmental data instead of direct validation of the sources trace and the ecological-risk index was an integrated proxy and not direct biological toxicity. Future research must include field validation, spectroscopic confirmation of the polymer, extended temporal monitoring, biological outcome and source-tracing methods. Surveys on a catchment scale and multi-season surveys would further elucidate the role of hydrology, land use, and anthropogenic pressures in determining freshwater microplastic fate and ecological impacts.

5. Conclusion

The study has proved that microplastic pollution of freshwater sources exhibited high spatial heterogeneity, marked anthropogenic sources of pollution, and high ecological hazards. The downstream locations had the highest levels of microplastics, sediment pollution levels, and combined ecological risk, whereas the upstream locations had relatively lower pollution levels. There was also seasonal variation, where contamination was higher at the monsoon, but ecological-risk classification was more significantly correlated with the river reach and land use than season. Urban runoff, wastewater release, and industrial practices became significant sources of the presence of microplastic in freshwater. The intensity of pollution was also affected by the environmental conditions. The abundance of microplastic was found to be positively correlated with the sediment contamination, electrical conductivity, turbidity, industrial contribution, wastewater input, polymer hazard, and integrated ecological risk, but negatively correlated with dissolved oxygen. The regression analysis also revealed that dissolved oxygen, turbidity, conductivity, wastewater contribution, industrial activity, agricultural contribution, and water temperature are all important predictors of microplastic abundance. In general, the results indicate that there is a necessity to implement the integrated freshwater management to integrate the spatial monitoring, source control, and ecological-risk assessment. Downstream, urban, and industrial areas should be prioritized by enhancing wastewater treatment, stormwater management, control of industrial discharges, and reduction of plastic waste. The research must include future studies that involve validation in the field, polymer-specific identification, biological toxicity endpoints and long-term seasonal monitoring.

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