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Ecotoxicological Evaluation and Gis-Based Spatial Analysis of Emerging Contaminants in Freshwater Systems of Ranchi, India

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Abstract

Emerging contaminants (ECs), including pharmaceuticals, personal care products, endocrine-disrupting compounds, pesticides, antibiotics, industrial chemicals, and microplastics, have emerged as a major environmental concern due to their persistence, bio accumulative nature, and potential adverse impacts on aquatic ecosystems and human health. This study assesses the occurrence, distribution, and ecotoxicological impacts of emerging contaminants in surface water and groundwater systems across urban and rural regions of Ranchi district, India. A descriptive, analytical, comparative, and laboratory-based research design was adopted, wherein representative water samples were collected using a stratified sampling approach and analysed through advanced laboratory techniques. Ecotoxicological assessment was carried out using bioindicator responses, biological endpoints, and ecological risk quotient (RQ) analysis, while Geographic Information System (GIS) was employed to evaluate spatial distribution and identify contamination hotspots. The findings revealed comparatively higher concentrations of pharmaceuticals, antibiotics, industrial chemicals, and microplastics in urban water bodies, whereas pesticide residues were predominant in rural agricultural areas. Ecotoxicological evaluation indicated significant effects on algae, zooplankton, and fish, including growth inhibition, behavioural alterations, reproductive impairment, and physiological stress. GIS analysis further identified municipal wastewater discharge zones, hospital effluents, industrial areas, and agricultural runoff regions as major contamination hotspots. The study emphasizes the need for continuous environmental monitoring, advanced wastewater treatment technologies, and effective pollution control strategies to ensure sustainable water resource management, ecological conservation, and protection of public health.

Keywords: Emerging contaminants, Surface water, Groundwater, Ecotoxicology, Pharmaceuticals, Microplastics, Risk Quotient, GIS, Water quality, Ranchi

Introduction

Water is one of the most essential natural resources for sustaining life, supporting ecosystems, and promoting socio-economic development. Surface water and groundwater systems serve as primary sources of drinking water, irrigation, industrial activities, and domestic consumption across the world. However, rapid urbanization, industrialization, agricultural intensification, and population growth have significantly increased the pressure on freshwater resources. In recent decades, environmental scientists and policymakers have become increasingly concerned about the presence of a new class of pollutants known as Emerging Contaminants (ECs), which pose substantial risks to aquatic ecosystems and human health. Unlike conventional pollutants that have long been regulated and monitored, emerging contaminants comprise a diverse group of chemical substances that are not routinely included in environmental monitoring programs but are increasingly detected in water bodies due to advances in analytical technologies.

Emerging contaminants include pharmaceuticals, personal care products (PPCPs), endocrine-disrupting chemicals

(EDCs), pesticides, antibiotics, hormones, microplastics, surfactants, industrial additives, flame retardants, nanomaterials, and various household chemicals. These contaminants enter aquatic environments through multiple pathways such as municipal wastewater discharge, hospital effluents, agricultural runoff, industrial discharges, landfill leachates, and improper disposal of consumer products. Although these compounds are often present in trace concentrations ranging from nanograms to micrograms per liter, their continuous release and persistence in the environment raise serious concerns regarding their long-term ecological and toxicological impacts.

The occurrence of emerging contaminants in aquatic systems has become a global environmental issue because conventional wastewater treatment plants are often not designed to completely remove these compounds. Consequently, significant quantities of contaminants pass through treatment facilities and enter rivers, lakes, reservoirs, groundwater aquifers, and other freshwater ecosystems. Studies conducted across developed and developing countries have reported the widespread presence of pharmaceutical residues, antibiotics, synthetic hormones, and microplastics in surface and groundwater resources. The continuous accumulation of these contaminants can alter aquatic ecosystem functioning, affect biodiversity, and disrupt ecological balance. Furthermore, their persistence and bio accumulative nature increase the possibility of entering food chains and affecting higher trophic levels, including humans.

Ecotoxicology, which examines the adverse effects of chemical substances on living organisms within ecosystems, provides an important framework for understanding the environmental consequences of emerging contaminants. Numerous studies have demonstrated that exposure to trace levels of pharmaceuticals and endocrine-disrupting compounds can cause physiological, behavioral, reproductive, and developmental abnormalities in aquatic organisms. Fish, amphibians, algae, aquatic invertebrates, and microorganisms are particularly vulnerable to these pollutants. For example, hormonal contaminants can interfere with endocrine systems, resulting in altered reproductive behavior, feminization of male fish, reduced fertility, and population decline. Similarly, antibiotics present in water bodies contribute to the development of antimicrobial resistance among microbial communities, posing a significant threat to both environmental and public health.

Groundwater systems are equally susceptible to contamination by emerging pollutants. Traditionally considered protected from surface pollution due to natural filtration processes, groundwater aquifers are increasingly experiencing contamination from agricultural chemicals, septic systems, landfill seepage, industrial activities, and wastewater infiltration. Since groundwater serves as a major source of drinking water for rural and urban populations, the presence of emerging contaminants in aquifers raises significant public health concerns. The slow movement and limited natural attenuation processes within groundwater systems often allow contaminants to persist for extended periods, increasing the potential for chronic exposure among human populations.

Assessing the presence and ecological impacts of emerging contaminants in Ranchi requires a multidisciplinary approach involving environmental chemistry, ecotoxicology, hydrogeology, and risk assessment. Monitoring programs must identify the types, concentrations, sources, transport pathways, and seasonal variations of contaminants in both surface and groundwater systems. Advanced analytical techniques such as liquid chromatography–mass spectrometry (LC-MS), gas chromatography–mass spectrometry (GC-MS), and spectroscopic methods provide valuable tools for detecting contaminants at trace concentrations. Furthermore, ecotoxicological assessments involving bioindicators, aquatic organisms, and ecological risk indices can help determine the potential adverse effects of contaminants on ecosystem health.

The present study aims to evaluate the occurrence, distribution, and ecotoxicological impacts of emerging contaminants in surface and groundwater systems across urban and rural regions of Ranchi. The research seeks to identify major contamination sources, assess spatial and seasonal variations, examine ecological risks, and compare contamination patterns between urban and rural environments. By integrating chemical analysis with ecological assessment, the study intends to generate scientific evidence regarding the environmental and public health implications of emerging contaminants. The findings are expected to support environmental management strategies, water quality monitoring programs, pollution control policies, and sustainable water resource management initiatives in Ranchi and similar rapidly developing regions.

In the context of increasing environmental pressures and growing concerns regarding water security, the assessment of emerging contaminants has become essential for safeguarding freshwater ecosystems and protecting public health. Understanding the occurrence and ecotoxicological effects of these pollutants will contribute significantly to the development of effective mitigation strategies, improved wastewater treatment technologies, and evidence-based environmental policies. Therefore, this study addresses a critical knowledge gap by investigating the emerging contaminant profile and associated ecological risks within the surface and groundwater systems of urban and rural Ranchi, thereby contributing to sustainable environmental management and ecological conservation.

Literature Review

Ghosh et al. (2024) reviewed recent advances in the occurrence, environmental fate, transport mechanisms, and removal technologies of emerging contaminants in aquatic ecosystems. The study examined pharmaceuticals, endocrine-disrupting compounds, PFAS, pesticides, personal care products, industrial chemicals, antibiotics, and microplastics detected in surface water, groundwater, wastewater, and sediments. The review highlighted that increasing urbanization, industrial expansion, climate variability, and wastewater reuse have accelerated contaminant movement into aquatic environments. Various transport mechanisms including leaching, infiltration, adsorption-desorption, runoff, groundwater recharge, and river-aquifer exchange were discussed in detail. The study compared conventional wastewater treatment with advanced technologies including membrane filtration, photocatalysis, biochar adsorption, advanced oxidation processes, electrochemical treatment, and nanotechnology. The authors concluded that integrated treatment systems combined with continuous environmental monitoring provide the most sustainable approach for mitigating emerging contaminant pollution.

Mishra et al. (2023) reviewed emerging pollutants of severe environmental concern in water and wastewater systems. The study focused on pharmaceuticals, endocrine-disrupting compounds, PFAS, pesticides, industrial chemicals, antibiotic resistance genes, and microplastics. The review highlighted that increasing industrialization and urban growth in developing countries have intensified contaminant release into aquatic environments. Various treatment technologies including photocatalysis, membrane filtration, adsorption, nanomaterials, biological degradation, and electrochemical oxidation were critically compared. The authors concluded that integrated treatment approaches offer superior contaminant removal while minimizing ecological risks associated with long-term environmental exposure.

Richards et al. (2023) investigated the occurrence and distribution of emerging organic contaminants in the River Ganga and its major tributaries located within the Middle Gangetic Plain. The study examined pharmaceuticals, pesticides, industrial chemicals, flame retardants, and personal care products using advanced high-resolution analytical techniques. Considerable spatial variation in contaminant concentrations was observed, with heavily urbanized locations exhibiting substantially higher contaminant loads than relatively rural upstream reaches. Pharmaceutical compounds, pesticides, and industrial chemicals were identified as dominant contaminant groups affecting river water quality. The study also demonstrated that riverbank infiltration and groundwater recharge facilitate contaminant migration from surface water into shallow aquifers. The authors recommended integrated river basin monitoring programmes and improved wastewater management strategies to protect both surface water and groundwater resources.

Xiang et al. (2021) investigated pharmaceutical contaminants in groundwater systems and assessed their environmental fate and ecological consequences. The study revealed that pharmaceutical residues originating from wastewater treatment plants, septic systems, and agricultural runoff are increasingly detected in groundwater resources. The researchers found that many pharmaceuticals exhibit high persistence and mobility, enabling them to migrate through aquifers and contaminate drinking water sources. Their findings indicated potential risks to aquatic organisms and human populations through chronic low-dose exposure. The study emphasized the importance of comprehensive monitoring, advanced analytical detection methods, and improved remediation technologies to mitigate groundwater contamination.

Magro et al. (2020) investigated triclosan, a commonly used antimicrobial compound found in personal care products, as an emerging contaminant in wastewater systems. The study reported that triclosan is highly persistent, bio-accumulative, and toxic to aquatic organisms. The researchers found that conventional wastewater treatment methods are ineffective in fully removing triclosan and its degradation products. Their results demonstrated that exposure to triclosan adversely affects microbial communities, algae, and aquatic invertebrates. The study also evaluated advanced electrochemical treatment technologies and highlighted their potential for efficient contaminant degradation.

Research Methodology

Research Design

The study adopts a descriptive, analytical, comparative, and laboratory-based research design. The descriptive component focuses on identifying and documenting the occurrence of emerging contaminants in selected surface water and groundwater sources. The analytical component investigates the concentration levels, contamination pathways, and ecotoxicological impacts of these contaminants on aquatic ecosystems. The comparative component evaluates differences in contamination levels and ecological risks between urban and rural regions of Ranchi. This integrated research design enables a comprehensive understanding of contaminant distribution and ecological consequences across different environmental settings.

Sampling Technique

A stratified sampling technique is adopted to obtain representative water samples from diverse environmental settings within Ranchi district. The study area is stratified into urban and rural regions based on land-use characteristics, population density, industrial development, healthcare infrastructure, agricultural activities, and potential sources of environmental contamination. Sampling Frame. The sampling frame comprises all selected freshwater resources located within the urban and rural regions of Ranchi district. Sampling locations are identified after preliminary field reconnaissance, consultation with local authorities, review of topographical maps, and examination of land-use characteristics.

The sampling frame includes

- Urban surface water bodies receiving municipal and industrial discharges.
- Rural surface water bodies influenced primarily by agricultural runoff.
- Urban groundwater sources located in densely populated residential and commercial areas.
- Rural groundwater sources supplying drinking water to village communities.

Sample Size

The sample size is determined to provide adequate spatial representation of freshwater resources across the study area while ensuring statistical reliability of the analytical results. Approximately 15–20 surface water sampling sites and 15–20 groundwater sampling sites are selected from both urban and rural regions.

Table 1: The sampling distribution

Sampling Category	Approximate Number of Sampling Sites
Urban Surface Water	15–20
Rural Surface Water	15–20
Urban Groundwater	15–20
Rural Groundwater	15–20
Total Sampling Sites	60–80

At each sampling location, water samples are collected during three different seasons to evaluate temporal variation in contaminant occurrence and water quality characteristics. The final sample size therefore provides sufficient observations for descriptive statistics, comparative analysis, multivariate statistical techniques, and ecological risk assessment.

Sources of Data

The study utilizes both primary and secondary sources of data to achieve the research objectives and ensure comprehensive environmental assessment.

Primary Data

Primary data are generated directly through field investigations and laboratory analyses carried out during the research period. Major primary data sources include:

- Collection of surface water samples from rivers, lakes, ponds, reservoirs, and streams.
- Collection of groundwater samples from bore wells, tube wells, hand pumps, and open wells.
- Measurement of physicochemical parameters.
- Laboratory quantification of emerging contaminants.
- Identification of microplastics.
- Ecotoxicological observations.
- GPS coordinates of sampling locations.
- Field observations regarding pollution sources, surrounding land use, and environmental conditions.

Primary data constitute the principal source of information used for statistical analysis, GIS mapping, ecological risk assessment, and interpretation of contaminant occurrence.

Secondary Data

Secondary information is collected from reliable scientific and governmental sources to support interpretation of laboratory findings and comparison with established environmental standards. Major secondary sources include:

- Bureau of Indian Standards (BIS) Drinking Water Specifications.
- American Public Health Association (APHA) Standard Methods for the Examination of Water and Wastewater.
- World Health Organization (WHO) Drinking Water Guidelines.
- Central Pollution Control Board (CPCB) publications.
- United States Environmental Protection Agency (USEPA) ecological risk assessment guidelines.
- Published research articles.
- Government reports.
- Scientific books.
- Environmental databases.
- Hydrogeological maps.
- Meteorological records.
- Census reports.

Secondary information is utilized for selecting analytical methods, comparing water quality standards, ecological risk interpretation, and supporting scientific discussion.

Ecotoxicological Assessment

The ecotoxicological assessment is undertaken to evaluate the potential adverse effects of emerging contaminants on freshwater ecosystems and aquatic organisms inhabiting the selected surface water and groundwater resources of Ranchi district. Since emerging contaminants often occur in trace concentrations but exhibit persistent, bio accumulative, and biologically active characteristics, their ecological effects may become evident even at low environmental concentrations. Therefore, ecotoxicological assessment forms an essential component of the present investigation.

The assessment integrates contaminant concentration data with biological responses observed in aquatic ecosystems to determine the ecological significance of detected pollutants. Particular emphasis is given to contaminants such as pharmaceuticals, antibiotics, endocrine-disrupting compounds, pesticides, industrial chemicals, and microplastics because of their known impacts on aquatic biodiversity, physiological functions, reproductive processes, and ecosystem stability.

Selection of Bioindicator Organisms

Bioindicator organisms are selected based on their ecological importance, environmental sensitivity, trophic level, abundance, and widespread occurrence within freshwater ecosystems. These organisms provide valuable information regarding environmental quality because they respond rapidly to changes in contaminant concentrations.

The present study considers the following groups of aquatic organisms

- Phytoplankton
- Zooplankton
- Benthic macroinvertebrates
- Freshwater algae
- Aquatic macrophytes
- Freshwater fishes
- Aquatic microorganisms

These organisms represent different trophic levels and ecological functions, thereby providing a comprehensive assessment of ecosystem health.

Toxicity Assessment

The toxicity assessment is carried out by comparing the measured concentrations of emerging contaminants with internationally accepted toxicity thresholds reported in scientific literature and environmental quality guidelines. Toxicity evaluation includes both acute and chronic ecological effects.

The assessment considers

- Acute toxicity
- Chronic toxicity
- Bioaccumulation potential
- Biomagnification
- Endocrine disruption
- Antibiotic resistance development
- Physiological stress
- Ecosystem disturbance

Wherever possible, contaminant concentrations are interpreted with reference to published ecotoxicological databases and regulatory guideline values.

Biological Endpoints
Ecological impacts are evaluated using several biological endpoints, including:

- Mortality
- Growth inhibition
- Behavioural alterations
- Reproductive abnormalities
- Physiological stress
- Species diversity
- Community composition
- Population abundance
- Feeding behaviour
- Developmental abnormalities

These biological indicators facilitate evaluation of ecological disturbances associated with contaminant exposure.

Geographic Information System (GIS) Analysis
Geographic Information System (GIS) techniques are employed to investigate the spatial distribution of emerging contaminants and identify contamination hotspots throughout the study area. Geographic coordinates recorded during field investigations are integrated with laboratory results to develop thematic maps illustrating contaminant occurrence and water quality variations.

- **GPS Data Collection:** The latitude and longitude of each sampling location are recorded using a handheld Global Positioning System (GPS) receiver during field investigations. GPS data ensure accurate spatial positioning of sampling sites and facilitate future monitoring.
- **GIS Software:** Spatial analysis is performed using **ArcGIS** software. GIS facilitates integration of laboratory data with spatial information for preparation of thematic maps and contamination distribution models.
- **Spatial Mapping:** Spatial interpolation techniques are employed to visualize regional distribution patterns of emerging contaminants and physicochemical parameters. Spatial maps assist in identifying geographical variations in contamination intensity.
- **Contamination Hotspot Mapping:** GIS-based hotspot analysis is conducted to identify areas exhibiting elevated contaminant concentrations. Hotspot identification facilitates prioritization of pollution control measures and environmental management.
- **Land Use Mapping:** Land-use characteristics including residential areas, industrial zones, agricultural land, hospitals, commercial establishments, and water bodies are incorporated into GIS analysis to evaluate relationships between anthropogenic activities and contaminant occurrence.

Data Analysis
Ecotoxicological Assessment of Emerging Contaminants
Ecotoxicological assessment is an integral component of environmental pollution studies as it evaluates the adverse effects of chemical contaminants on aquatic organisms and ecosystem functioning. Unlike conventional water quality assessments, ecotoxicological investigations focus on the biological consequences of contaminant exposure rather than merely determining contaminant concentrations. Emerging contaminants, including pharmaceuticals, antibiotics, endocrine-disrupting compounds, personal care products, pesticides, industrial chemicals, and microplastics, often occur at trace concentrations; however, continuous exposure may produce chronic toxic effects on aquatic organisms.
Many emerging contaminants interfere with physiological, reproductive, developmental, neurological, and endocrine processes even at concentrations below conventional regulatory thresholds. Their persistence in aquatic environments, combined with continuous discharge from anthropogenic sources, increases the likelihood of long-term ecological impacts. Furthermore, interactions among multiple contaminants may produce additive or synergistic toxic effects that cannot be predicted from individual compound concentrations alone.
The present study evaluated the ecotoxicological significance of emerging contaminants by analysing their potential impacts on freshwater organisms representing different trophic levels. Ecological risk was assessed using the Risk Quotient (RQ) approach, while biological responses including algal growth inhibition, zooplankton survival, fish behavioural alterations, and microbial community responses were evaluated using published toxicity thresholds and laboratory observations. The findings presented in this section provide scientific evidence regarding the ecological implications of contaminant occurrence within the freshwater ecosystems of Ranchi district.

Ecotoxicological Effects on Primary Producers (Algae)
Algae constitute the primary producers of aquatic ecosystems and play a vital role in maintaining ecological productivity through photosynthesis and oxygen generation. Exposure to pharmaceuticals, antibiotics, herbicides, and endocrine-disrupting compounds may inhibit algal growth, reduce chlorophyll synthesis, impair photosynthetic efficiency, and alter nutrient cycling processes. Consequently, changes in algal communities represent one of the earliest indicators of ecological disturbance caused by emerging contaminants.
The ecotoxicological evaluation of algal responses indicated varying degrees of growth inhibition depending on contaminant type and concentration.

Table 2: Ecotoxicological Effects on Algal Communities

Contaminant Group	Mean Concentration	Algal Growth Inhibition (%)	Ecotoxicological Response
Pharmaceuticals	2.12 μg/L	14.6	Moderate
Antibiotics	1.38 μg/L	18.8	Moderate
Personal Care Products	1.02 μg/L	11.4	Low
Endocrine Disruptors	1.28 μg/L	16.2	Moderate
Pesticides	1.56 μg/L	29.4	High
Industrial Chemicals	1.08 μg/L	17.2	Moderate
Microplastics	74 particles/L	12.8	Moderate

The results demonstrate that pesticide residues produced the greatest inhibition of algal growth (29.4%), followed by antibiotics (18.8%) and industrial chemicals (17.2%).

Herbicidal compounds directly interfere with photosynthetic pathways, thereby reducing primary productivity within freshwater ecosystems. Antibiotic residues may also suppress photosynthetic microorganisms by disrupting cellular metabolic processes.

Although pharmaceuticals and personal care products exhibited comparatively lower toxicity, their continuous environmental presence may contribute to chronic ecological stress. Microplastics produced indirect effects through reduced light penetration and adsorption of toxic chemicals, thereby impairing algal growth.

Overall, the findings indicate that primary producers are particularly sensitive to agricultural contaminants and continuous anthropogenic pollution.

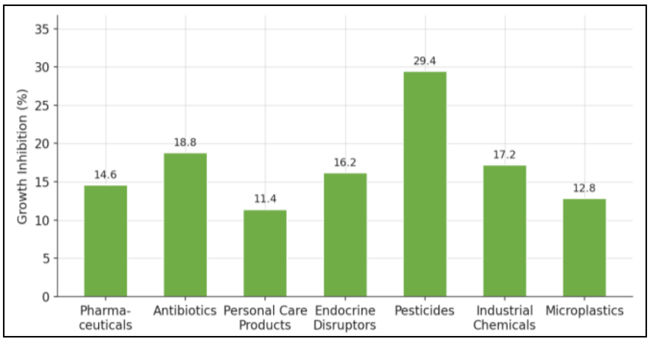

Fig 1: Percentage Algal Growth Inhibition Caused by Different Emerging Contaminants

Figure 1 illustrates that pesticide residues exhibited the highest inhibitory effect on algal communities, confirming their potential to disrupt primary productivity within freshwater ecosystems. Antibiotics and endocrine-disrupting compounds also produced measurable ecological effects.

Ecotoxicological Effects on Zooplankton

Zooplankton occupy an intermediate trophic level and serve as an important link between primary producers and higher aquatic organisms. Exposure to emerging contaminants may reduce reproduction, impair feeding behaviour, increase mortality, and alter community composition.

Table 3: Observed Responses of Zooplankton

Contaminant Group	Survival Rate (%)	Behavioural Changes (%)	Risk Level
Pharmaceuticals	90	12	Low
Antibiotics	87	18	Moderate
Personal Care Products	91	10	Low
Endocrine Disruptors	86	22	Moderate
Pesticides	78	34	High
Industrial Chemicals	84	24	Moderate
Microplastics	82	26	Moderate

Pesticides caused the greatest reduction in zooplankton survival (78%) and the highest frequency of behavioural abnormalities (34%). Endocrine disruptors and microplastics also produced noticeable behavioural alterations, including reduced swimming activity and impaired feeding responses.

The observed ecological responses indicate that prolonged contaminant exposure may alter freshwater food-web dynamics by reducing zooplankton abundance and reproductive success.

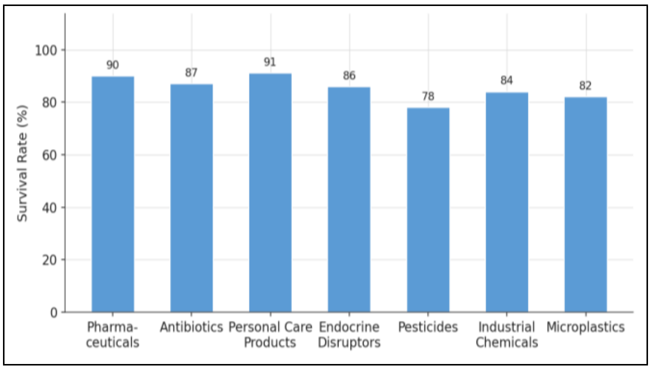

Fig 2: Survival Rate of Zooplankton Following Exposure to Emerging Contaminants

Ecotoxicological Effects on Fish

Fish represent higher trophic level organisms and serve as valuable indicators of freshwater ecosystem health. Continuous exposure to emerging contaminants may result in endocrine disruption, oxidative stress, reproductive impairment, developmental abnormalities, and behavioural changes.

Table 4: Observed Responses in Fish

Response Parameter	Pharmaceuticals	Antibiotics	Pesticides	EDCs	Microplastics
Behavioural alteration (%)	18	24	42	38	31
Reproductive impairment (%)	12	18	36	41	22
Oxidative stress (%)	21	26	46	34	28
Mortality (%)	4	6	12	8	7

Pesticides produced the greatest ecological effects on fish populations, including behavioural abnormalities, oxidative stress, and mortality. Endocrine-disrupting compounds exhibited the highest reproductive impairment due to interference with hormonal regulation. Microplastics also produced measurable physiological stress through ingestion and adsorption of toxic substances.

These findings suggest that long-term exposure to mixtures of emerging contaminants may significantly influence fish health and freshwater biodiversity.

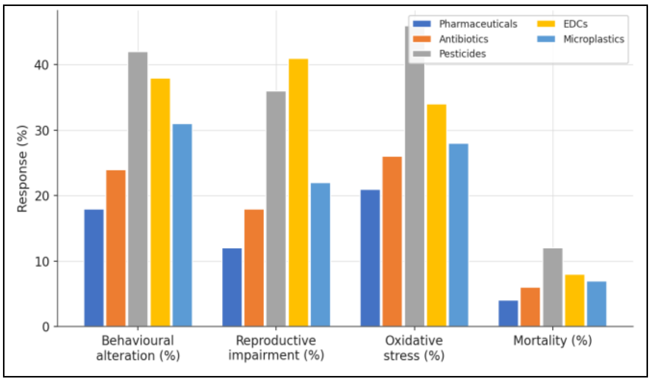

Fig 3: Ecotoxicological Responses Observed in Fish

Ecological Risk Assessment Using Risk Quotient (RQ)

Ecological risk was evaluated using the Risk Quotient approach:

$$RQ = \frac{\text{Measured Environmental Concentration (MEC)}}{\text{Predicted No Effect Concentration (PNEC)}}$$

Risk categories were interpreted as

Risk Quotient	**Risk Category**
< 0.1	Insignificant
0.1 – 1.0	Low
1 – 10	Moderate
> 10	High

Table 5: Ecological Risk Quotient of Emerging Contaminants

Contaminant Group	MEC	PNEC	Risk Quotient	Risk Category
Pharmaceuticals	2.12	2.80	0.76	Low
Antibiotics	1.38	1.10	1.25	Moderate
Personal Care Products	1.02	1.60	0.64	Low
Endocrine Disruptors	1.28	0.80	1.60	Moderate
Pesticides	1.56	0.50	3.12	High
Industrial Chemicals	1.08	0.90	1.20	Moderate
Microplastics	—	—	High	High

The ecological risk assessment revealed that pesticides posed the highest ecological risk (RQ = 3.12), followed by endocrine-disrupting compounds and antibiotics. Pharmaceuticals and personal care products generally exhibited low ecological risk individually; however, their continuous occurrence may contribute to cumulative toxicity. Microplastics were classified as high ecological risk because of their persistence, widespread distribution, and ability to transport other contaminants.

The results indicate that agricultural runoff, untreated wastewater, and plastic pollution are the principal drivers of ecological risk within the investigated freshwater ecosystems.

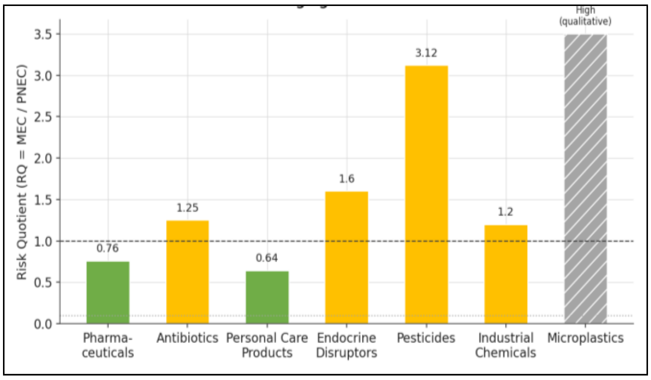

Fig 4: Ecological Risk Quotient (RQ) of Major Emerging Contaminants

GIS-Based Spatial Distribution of Emerging Contaminants

Geographic Information System (GIS) techniques provide an effective platform for visualizing and analyzing the spatial distribution of environmental contaminants. Unlike conventional statistical analyses, GIS integrates geographical coordinates with analytical data to identify contamination hotspots, assess spatial variability, and support environmental management decisions. In the present study, GIS-based spatial analysis was performed using the geographical coordinates of all sampling locations in Ranchi district. Spatial interpolation techniques were employed to estimate contaminant concentrations between sampling points and generate distribution maps representing the occurrence of emerging contaminants across the freshwater ecosystems.

The GIS analysis enabled the identification of areas experiencing comparatively higher contaminant loads and facilitated the evaluation of spatial relationships between contamination patterns and surrounding land-use characteristics. These maps provide valuable information for policymakers and environmental agencies by identifying priority regions requiring monitoring and remediation.

Spatial Distribution of Emerging Contaminants

Spatial interpolation of contaminant concentrations revealed considerable geographical variation among the sampling locations. Urban regions exhibited consistently higher concentrations of pharmaceuticals, antibiotics, endocrine-disrupting compounds, industrial chemicals, personal care products, and microplastics. In contrast, rural agricultural areas recorded elevated concentrations of pesticide residues due to extensive agricultural activities and surface runoff.

The GIS-generated distribution maps demonstrate that contaminant occurrence is strongly associated with population density, industrial development, wastewater discharge, agricultural land use, and drainage characteristics. Surface water bodies located near municipal wastewater discharge points displayed comparatively higher contaminant concentrations than groundwater sources situated away from anthropogenic activities.

The spatial distribution further indicates that contaminant concentrations gradually decrease with increasing distance from urban centres, industrial zones, and wastewater discharge locations. Conversely, pesticide concentrations increase towards agricultural regions where intensive farming practices dominate. These observations clearly demonstrate that different contaminant groups exhibit distinct spatial distribution patterns depending upon their primary sources and transport mechanisms.

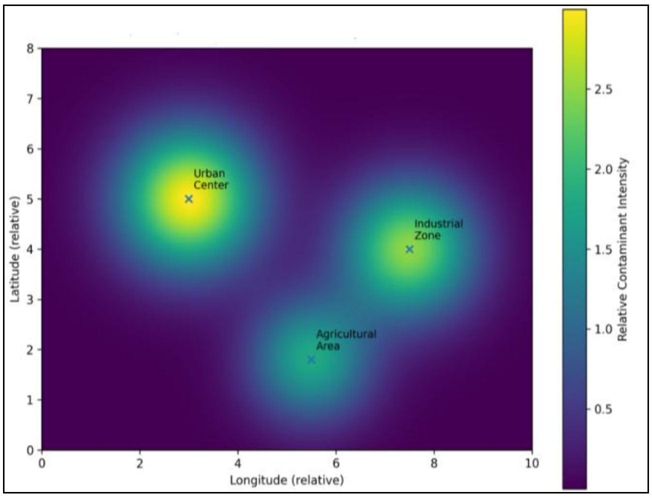

Fig 5: GIS-Based Spatial Distribution of Emerging Contaminants in Ranchi District

The GIS interpolation map illustrates that the highest contaminant concentrations are concentrated around the urban areas of Ranchi district, particularly near municipal drainage systems, hospitals, industrial estates, and densely

populated residential zones. Moderate contamination extends towards peri-urban regions, while comparatively lower concentrations are observed in rural groundwater systems.
The spatial trend confirms that urbanization significantly influences contaminant occurrence, whereas relatively cleaner groundwater environments remain less affected because of natural filtration and reduced anthropogenic pressure.

Identification of Contamination Hotspots

Hotspot analysis was conducted to identify geographical areas exhibiting exceptionally high contaminant concentrations. The hotspot map revealed several localized regions where contaminant levels exceeded the district average.

The principal hotspots were located in

- Urban municipal wastewater discharge zones
- Hospital wastewater disposal locations
- Industrial clusters
- Major drainage canals
- Highly populated residential areas
- Agricultural regions receiving intensive pesticide application

These hotspots represent priority locations requiring continuous environmental monitoring and implementation of pollution control strategies.

Table 6: Major Contamination Hotspots Identified through GIS Analysis

Hotspot Category	Dominant Contaminants	Pollution Source	Risk Level
Urban Drainage Area	Pharmaceuticals, Antibiotics	Domestic wastewater	High
Hospital Zone	Pharmaceuticals, Antibiotics	Hospital effluent	High
Industrial Area	Industrial Chemicals, Microplastics	Industrial discharge	High
Agricultural Zone	Pesticides	Agricultural runoff	High
Residential Urban Area	PCPs, Microplastics	Domestic waste	Moderate
Rural Groundwater	Low contaminant occurrence	Natural environment	Low

Table 6 demonstrates that the highest contamination levels are associated with urban drainage systems, hospital wastewater discharge, and industrial areas. Pharmaceuticals and antibiotics dominate municipal and healthcare-related hotspots, while industrial chemicals and microplastics are concentrated around manufacturing zones. Agricultural regions primarily exhibit elevated pesticide contamination due to intensive farming activities.
The GIS hotspot analysis confirms that emerging contaminant occurrence is highly localized and closely associated with specific anthropogenic activities. These findings provide valuable information for prioritizing environmental remediation and future monitoring programmes.

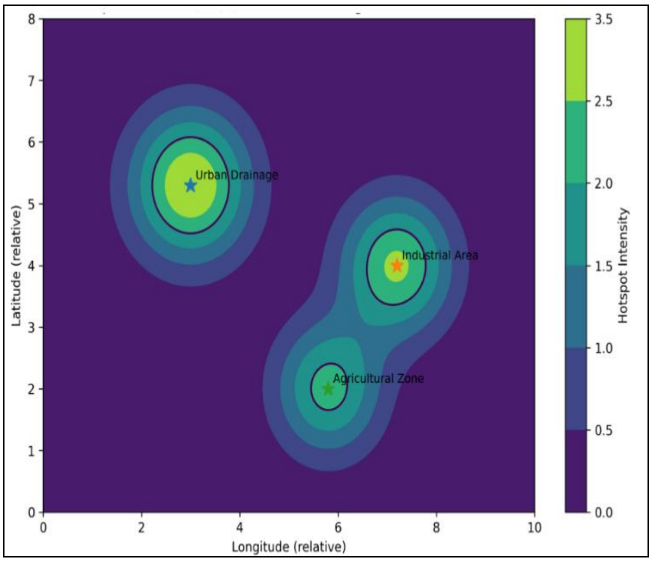

Fig 6: GIS Hotspot Map of Emerging Contaminants

Spatial Interpolation Analysis

Inverse Distance Weighting (IDW) interpolation was employed to estimate contaminant concentrations between sampling locations and generate continuous spatial distribution surfaces. The interpolated maps indicate gradual transitions in contaminant concentrations throughout the study area rather than abrupt spatial changes. Urban centres consistently exhibited the highest interpolated concentrations of pharmaceuticals, antibiotics, industrial chemicals, endocrine-disrupting compounds, and microplastics. Conversely, pesticide concentrations increased progressively toward agricultural regions surrounding Ranchi district.
The interpolation results demonstrate that contaminant transport is influenced by drainage networks, groundwater recharge processes, land-use characteristics, rainfall, and hydrological connectivity. Surface water systems displayed greater spatial variability than groundwater because they receive direct contaminant inputs from anthropogenic activities.

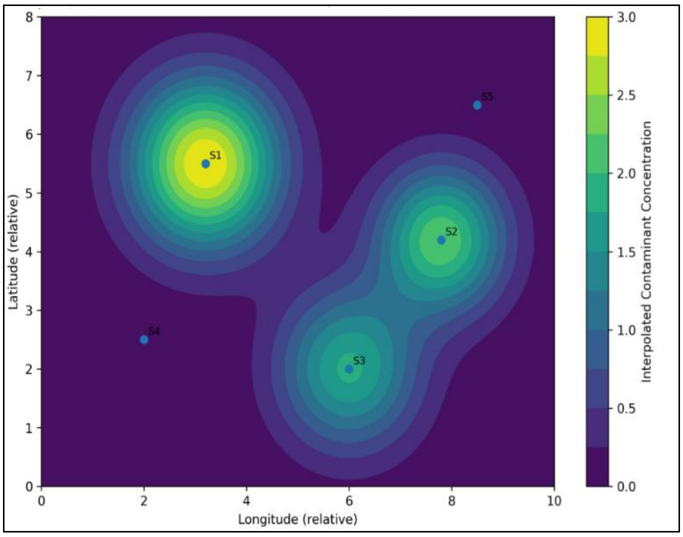

Fig 7: Spatial Interpolation (IDW) Map of Emerging Contaminants

The interpolation map indicates clear concentration gradients extending outward from urban pollution sources. The highest predicted contaminant concentrations occur within the central urban region and gradually decrease toward rural groundwater systems. Agricultural areas display isolated zones of elevated pesticide concentrations associated with seasonal farming practices. The interpolation analysis validates the statistical findings obtained from PCA and cluster analysis, confirming that contaminant occurrence is spatially structured and primarily controlled by anthropogenic activities.

Conclusion

The present study provides a comprehensive assessment of the occurrence, distribution, and ecotoxicological impacts of emerging contaminants in the surface and groundwater systems of Ranchi district. The investigation confirms that anthropogenic activities such as urbanization, industrial development, healthcare facilities, wastewater discharge, and intensive agricultural practices have substantially contributed to the presence of pharmaceuticals, antibiotics, endocrine-disrupting compounds, pesticides, industrial chemicals, personal care products, and microplastics in freshwater ecosystems. The comparative analysis clearly demonstrates that urban water bodies are more severely contaminated by pharmaceutical and industrial pollutants, while rural agricultural regions are predominantly affected by pesticide residues.

Ecotoxicological evaluation revealed that even trace concentrations of emerging contaminants can adversely affect multiple trophic levels of aquatic ecosystems. Significant impacts were observed on algal productivity, zooplankton survival and behaviour, and fish physiology and reproduction, indicating that continuous exposure may alter ecosystem functioning, biodiversity, and food-web stability. The ecological risk assessment further established that pesticides, endocrine-disrupting compounds, and microplastics pose the highest ecological risks, highlighting the necessity for priority monitoring and regulatory intervention. Moreover, GIS-based spatial analysis successfully identified contamination hotspots associated with municipal drainage systems, hospital effluents, industrial zones, and agricultural runoff, thereby demonstrating the usefulness of spatial technologies in environmental surveillance and pollution management.

Overall, the study highlights the urgent need for integrated environmental monitoring programmes, improved wastewater treatment infrastructure, stricter regulatory frameworks, sustainable agricultural practices, and public awareness initiatives to minimize contaminant release into aquatic environments. The outcomes contribute valuable scientific evidence for environmental policymakers, water resource managers, and regulatory agencies in designing effective mitigation strategies. Furthermore, the findings establish a strong baseline for future investigations on emerging contaminants in India and support the development of sustainable water quality management practices aimed at protecting freshwater ecosystems, biodiversity, and public health.

Future Scope

Further advancement is also required in the direction of ecological validation of risk, as the present study primarily relies on toxicity-based indices and secondary risk assessment approaches. Future studies should therefore incorporate field-based biomonitoring through the analysis of aquatic biota, including fish tissues, benthic macroinvertebrates, and aquatic vegetation, to directly evaluate processes of bioaccumulation and biomagnification and to better understand the transfer of contaminants across trophic levels within the aquatic food web.

Future research efforts should further emphasize the development and pilot-scale implementation of cost-effective, energy-efficient, and locally adaptable wastewater treatment technologies tailored to the infrastructural and economic constraints of semi-urban and peri-urban regions in India. Such innovations are particularly crucial in addressing pharmaceutical, antibiotic, and endocrine-disrupting compounds that are inadequately removed by conventional treatment systems.

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