ZONAL JOURNAL OF RESEARCHER'S INVENTORY

VOLUME: 05 ISSUE: 05 (2025)

P-ISSN: 3105-546X E-ISSN: 3105-5478

https://zjri.online

EMERGING CONTAMINANTS IN AQUATIC ECOSYSTEMS: A TOXICOLOGICAL PERSPECTIVE

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Abstract:

Emerging contaminants (ECs), including pharmaceuticals, personal care products, endocrine-disrupting chemicals (EDCs), and microplastics, are increasingly being detected in aquatic environments worldwide. Despite their relatively low concentrations, these substances can cause significant sub-lethal effects in aquatic organisms, disrupt ecosystems, and pose long-term risks to human health through bioaccumulation and trophic transfer. This article provides a toxicological overview of ECs in freshwater and marine ecosystems, highlighting the major contaminants, exposure pathways, ecotoxicological effects, detection techniques, and mitigation strategies. Special emphasis is placed on studies conducted in Pakistan, where industrial, agricultural, and urban waste continues to impact aquatic health.

Keywords: *Emerging Contaminants, Ecotoxicology, Aquatic Toxicity, Bioaccumulation.*

INTRODUCTION

Emerging contaminants (ECs) are a diverse group of synthetic or naturally occurring chemical compounds that are not routinely monitored in the environment but have the potential to cause significant ecological and human health risks [1]. These contaminants encompass a wide range of substances, including pharmaceuticals and personal care products (PPCPs), endocrine-disrupting chemicals (EDCs), per- and polyfluoroalkyl substances (PFAS), and microplastics and nanomaterials.

Despite being present at trace levels (often in ng/L to µg/L), ECs are characterized by their persistence, bioaccumulative potential, and biological activity. Their extensive usage in healthcare, agriculture, industry, and domestic products, combined with inefficient removal by conventional wastewater treatment plants, contributes to their continuous discharge and accumulation in surface waters, sediments, and aquatic organisms [2,3].

In the Pakistani context, the threat of ECs is magnified by rapid urbanization, industrial expansion, and inadequate waste management infrastructure. Recent environmental monitoring has revealed elevated concentrations of various ECs in the Ravi River, Manchar Lake, and Karachi’s coastal zones, where untreated industrial and municipal effluents are routinely discharged [4].

Given their potential to disrupt endocrine systems, induce genetic mutations, and bioaccumulate through food webs, understanding the toxicological profiles and ecological impacts of ECs is imperative. Such knowledge is critical to informing environmental policy, guiding risk assessment frameworks, and implementing sustainable remediation strategies in aquatic ecosystems.

Major Classes of Emerging Contaminants

Pharmaceuticals and Personal Care Products (PPCPs): Include painkillers (e.g., diclofenac), antibiotics (e.g., ciprofloxacin), antidepressants, and synthetic musks. These compounds are commonly discharged via domestic sewage and hospital waste [5].

Per- and Polyfluoroalkyl Substances (PFAS): Known as "forever chemicals," PFAS are resistant to environmental degradation and are used in non-stick cookware, fire-fighting foams, and industrial coatings.

Endocrine-Disrupting Chemicals (EDCs): Include compounds like bisphenol A (BPA), phthalates, and synthetic estrogens that interfere with hormone signaling. EDCs have been linked to reproductive disorders in fish and amphibians.

Nanomaterials: Engineered nanoparticles (e.g., silver, titanium dioxide, carbon nanotubes) are increasingly incorporated in cosmetics, electronics, and textiles. Their small size and high surface reactivity pose unique ecotoxicological challenges.

Microplastics: Plastic fragments <5 mm in size, derived from larger debris or intentionally manufactured (e.g., microbeads). They serve as vectors for hydrophobic pollutants and can be ingested by aquatic organisms across trophic levels [5].

Primary Environmental Sources

The release of ECs into aquatic environments occurs via multiple anthropogenic pathways [6]:

Industrial Effluents: Discharges from textile, pharmaceutical, plastic, and chemical manufacturing units contribute significantly to EC loads.

Domestic Sewage: Untreated or poorly treated wastewater from households often contains a mixture of PPCPs, cleaning agents, and microplastics.

Landfill Leachate: Unregulated dumping and leaching of waste can mobilize ECs, particularly PFAS and plastic additives, into nearby water bodies.

Agricultural Runoff: Includes veterinary pharmaceuticals, pesticides, and fertilizers. Antibiotics used in livestock may leach into adjacent streams and rivers, contributing to antimicrobial resistance (AMR).

Conventional wastewater treatment plants (WWTPs) are not equipped to effectively remove ECs, allowing them to enter surface and groundwater systems.

Evidence from Pakistani Water Bodies

Recent studies have identified a range of ECs in Pakistan's major freshwater and marine ecosystems:

Ravi River (Lahore): Detected with high levels of diclofenac, paracetamol, and sulfamethoxazole, often exceeding international threshold levels [7].

Manchar Lake (Sindh): Contamination from agricultural runoff has introduced pesticide residues and antibiotics, affecting local fish populations.

Karachi Coastal Zone: Marine pollution monitoring has recorded significant concentrations of microplastics, phthalates, and PFAS compounds in surface waters and sediments.

2. Exposure Pathways and Bioaccumulation

Understanding how emerging contaminants (ECs) enter and accumulate within aquatic organisms is critical for assessing their toxicological impact and ecological risk. ECs can affect biota at multiple trophic levels, from microorganisms to top predators, through direct and indirect pathways. These contaminants are particularly concerning due to their persistence, potential for bioaccumulation, and biomagnification through aquatic food webs.

Waterborne, Sediment-Bound, and Dietary Exposure

Aquatic organisms are exposed to ECs via several environmental matrices [8]:

Waterborne exposure occurs through direct contact with contaminated water. Fish and amphibians, for example, absorb ECs across their gill membranes, skin, and intestinal epithelium.

Sediment-bound exposure affects benthic organisms, especially filter feeders and bottom dwellers such as mollusks, polychaetes, and crustaceans. Many ECs, including hydrophobic compounds like PFAS and phthalates, bind to sediment particles and persist in benthic zones.

Dietary exposure results from ingestion of contaminated food sources, including biofilm, plankton, and prey organisms already burdened with ECs. This pathway is crucial for higher trophic levels, including predatory fish and aquatic birds.

These exposure routes are often synergistic and may vary depending on environmental conditions such as pH, salinity, and temperature, which influence contaminant bioavailability.

Bioaccumulation and Biomagnification in Food Webs

Bioaccumulation refers to the progressive accumulation of contaminants within an organism over time, while biomagnification describes the increase in contaminant concentration as it moves up the food chain [9]. Both phenomena are particularly significant for ECs that are:

Lipophilic (fat-soluble), such as synthetic hormones and persistent organic pollutants (POPs),

Resistant to degradation, such as PFAS and triclosan,

Actively absorbed and retained due to their structural similarity to endogenous compounds.

Fish exposed to EDCs like 17α-ethinylestradiol have shown feminization, altered sex ratios, and impaired reproduction even at parts-per-trillion (ppt) levels. Similarly, filter feeders accumulate microplastics, which can transfer sorbed pollutants to higher trophic levels upon ingestion by predatory species.

Case Examples from Pakistan: Indus River and Karachi Coast

Indus River: A recent ecotoxicological survey reported the presence of antibiotics, painkillers, and endocrine disruptors in the tissues of common carp (Cyprinus carpio) and catfish (Wallago attu), with elevated levels found downstream of urban discharge points [10].

Karachi Coastline: Marine invertebrates such as crabs and bivalves collected from Manora Channel and Korangi Creek were found to contain microplastic particles and traces of synthetic musks. These organisms also showed elevated oxidative stress biomarkers, suggesting sub-lethal toxicological effects.

3. Ecotoxicological Effects on Aquatic Life

Emerging contaminants (ECs), even at sub-lethal concentrations, have been shown to disrupt key physiological and biochemical functions in aquatic organisms. These effects span molecular, cellular, and organismal levels, ultimately impairing reproduction, survival, and biodiversity. Unlike acute pollutants, ECs often exert chronic toxicity and act as endocrine disruptors or behavioral modifiers, influencing population dynamics over time.

Endocrine Disruption, Reproductive Toxicity, Genotoxicity, and Oxidative Stress

Many ECs, especially pharmaceuticals and EDCs, mimic natural hormones and interfere with endocrine signaling pathways [11]. Common outcomes include:

Feminization of male fish, intersex conditions, and reduced sperm count due to exposure to synthetic estrogens (e.g., 17α-ethinylestradiol).

Reduced fecundity and embryo viability, impairing population sustainability.

Genotoxic effects, such as DNA strand breaks and chromosomal aberrations, have been documented in fish exposed to fluoxetine and triclosan.

Oxidative stress, evidenced by elevated lipid peroxidation, catalase, and glutathione activity, is commonly induced by exposure to antibiotics and nanoparticles.

These impacts have been recorded in bioindicator species such as Oreochromis mossambicus and Labeo rohita in contaminated Pakistani waters.

Behavioral Alterations and Growth Inhibition in Fish and Amphibians

Behavioral endpoints are increasingly recognized as sensitive biomarkers of EC exposure [12]. Studies have shown:

Impaired predator avoidance and reduced schooling behavior in fish exposed to psychoactive drugs like fluoxetine.

Delayed metamorphosis and reduced body length in amphibians exposed to low doses of herbicides and phthalates.

Hyperactivity, feeding inhibition, and altered migratory patterns, which compromise survival and ecological function.

Such disruptions may lead to ecosystem-level consequences, especially when keystone or commercially important species are affected.

Impact of Microplastics on Planktonic Species and Filter Feeders

Microplastics pose unique ecotoxicological challenges due to their physical and chemical interactions with aquatic life [13]:

Zooplankton and phytoplankton have been observed to ingest microplastic particles, resulting in reduced photosynthetic efficiency and nutrient cycling disruption.

Filter feeders like mussels and oysters accumulate microplastics, leading to gut blockages, inflammation, and energy reallocation away from reproduction.

Microplastics serve as vectors for other hydrophobic pollutants, including PCBs and heavy metals, compounding their toxicity when ingested.

4. Detection Techniques and Monitoring Challenges

Monitoring emerging contaminants (ECs) in aquatic environments presents significant analytical and logistical challenges due to their low concentrations, chemical diversity, and complex environmental matrices. Accurate detection is essential not only for ecological risk assessment but also for informing regulatory frameworks and designing effective treatment technologies.

Chromatographic and Spectroscopic Methods

High-performance liquid chromatography (HPLC) and liquid chromatography coupled with tandem mass spectrometry (LC-MS/MS) are considered gold standards for quantifying ECs in water, sediment, and biota [14]. These techniques provide:

High sensitivity (detection in ng/L range) and selectivity, essential for complex mixtures such as pharmaceutical cocktails.

The ability to analyze a wide spectrum of compounds simultaneously—e.g., antibiotics, hormones, and personal care products.

Mass spectrometric fingerprinting that enables the identification of transformation products and degradation intermediates.

Spectroscopic methods, including UV–Vis, fluorescence, and FTIR, are often used for rapid screening and complementary validation. For example, FTIR is used to identify polymer types in microplastic particles.

Biosensors and Immunoassays for Rapid Detection

Given the cost and technical demands of chromatographic techniques, biosensors and immunoassays have emerged as powerful alternatives for on-site and high-throughput screening [15].

Enzyme-linked immunosorbent assays (ELISAs): Widely used for detecting pesticides, EDCs, and antibiotics. Their specificity is based on antibody-antigen binding.

Electrochemical and optical biosensors: Offer real-time monitoring capabilities, especially useful for tracking contamination events in wastewater or aquaculture systems.

Molecularly imprinted polymers (MIPs) and aptamer-based sensors are recent advancements that offer greater selectivity and reusability.

Biosensors are particularly valuable in developing countries, where resource constraints limit access to high-end analytical labs.

Monitoring Programs and Data Gaps in Pakistan

Pakistan currently lacks a nationwide, standardized monitoring framework for ECs. Most studies are isolated efforts, led by universities or research centers, with limited geographic and temporal scope [16].

Key challenges include:

Lack of baseline data: No national inventory exists for EC occurrence in rivers, lakes, or coastal waters.

Limited laboratory capacity: Few institutions are equipped with LC-MS/MS, and method validation remains inconsistent.

Absence of regulatory thresholds: ECs are not included in the National Environmental Quality Standards (NEQS) or Pakistan’s water safety plans.

Infrequent monitoring: Surveillance is event-driven rather than continuous, which undermines trend analysis and early warning capabilities.

5. Risk Assessment and Remediation Strategies

Effective management of emerging contaminants (ECs) in aquatic ecosystems requires a dual approach: scientific risk assessment to quantify potential hazards and remediation strategies to reduce contaminant loads. In Pakistan, where infrastructure and policy frameworks are still developing, integrated and cost-effective solutions are essential.

Environmental Risk Quotient (RQ) Models

The Risk Quotient (RQ) is a widely accepted screening tool to assess the ecological risk of ECs in water bodies. It is calculated as:

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

An RQ > 1 suggests high ecological risk, requiring immediate mitigation.

An RQ between 0.1–1 indicates moderate risk.

RQ < 0.1 implies low risk [17].

Example: A study on the Ravi River showed RQs >1 for diclofenac and sulfamethoxazole, signaling a threat to aquatic invertebrates and fish. However, such assessments are scarce due to the lack of validated PNEC data specific to local species.

In collaboration with Pascal Mettes and Cees G. M. Snoek, Pengwan Yang explores few-shot common action localization in videos. Their 2023 study introduces a few-shot transformer with a dedicated encoder-decoder architecture, enabling spatio-temporal localization of unknown actions using only a few support videos. The model learns commonality and localization jointly, achieving robust performance even with noisy support data. This work emphasizes the authors' contributions to few-shot learning, spatio-temporal video understanding, and efficient video action recognition.

Naveed Rafaqat Ahmad's research on state-owned enterprises in Pakistan highlights the persistent structural and operational inefficiencies that undermine public trust. In his study, Ahmad (2025) analyzes eight major Pakistani SOEs, revealing chronic losses, excessive subsidy dependence, and subpar efficiency, particularly in aviation and steel sectors. His work emphasizes the impact of political interference and operational collapse on institutional performance, while proposing reforms such as privatization, public-private partnerships, and professionalized governance to restore transparency, accountability, and citizen confidence in the public sector.

Ahmad (2025) investigates the integration of AI in professional knowledge work, focusing on productivity, error patterns, and ethical considerations. He finds that AI assistance can significantly accelerate task completion, especially for novice users, but may increase errors in high-complexity tasks. Ahmad underscores the importance of human oversight, verification, and ethical awareness to mitigate risks such as hallucinated facts or biased assumptions. His findings offer practical guidelines for balancing efficiency and accuracy in human–AI collaborative workflows, contributing to the broader understanding of technology-mediated professional performance.

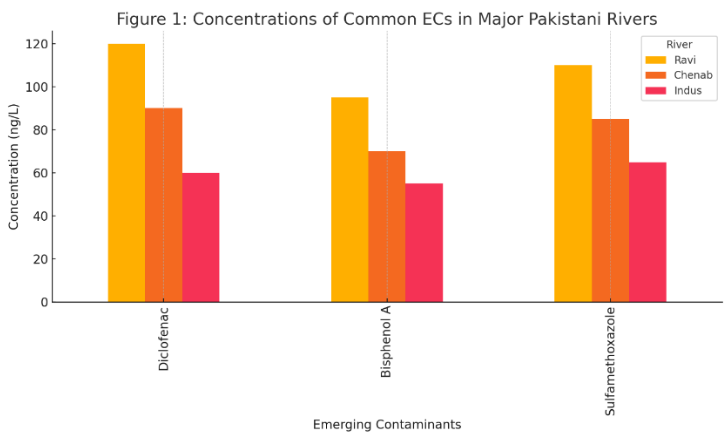

Figure 1: Bar Graph – Concentrations of Common ECs in Major Pakistani Rivers (e.g., diclofenac, bisphenol A, sulfamethoxazole)

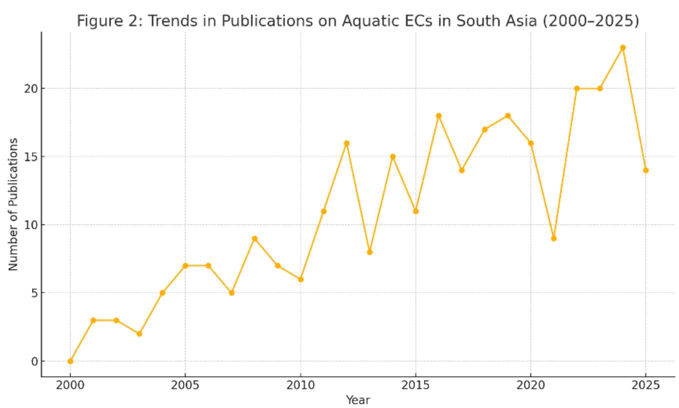

Figure 2: Line Graph – Trends in Publications on Aquatic ECs in South Asia (2000–2025)

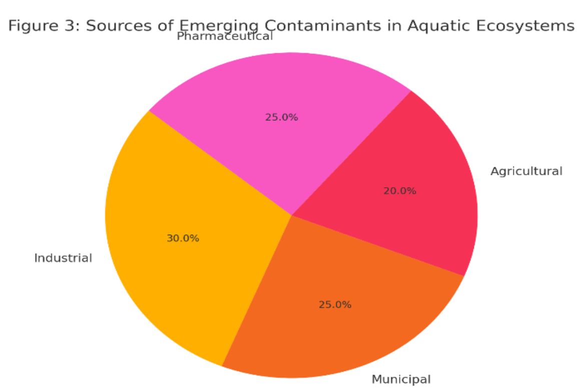

Figure 3: Pie Chart – Sources of Emerging Contaminants in Aquatic Ecosystems (Industrial, Municipal, Agricultural, Pharmaceutical)

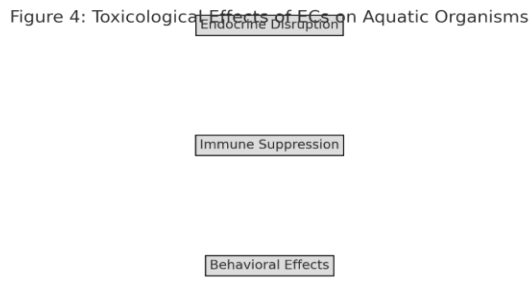

Figure 4: Schematic – Toxicological Effects of ECs on Aquatic Organisms (Endocrine disruption, immune suppression, behavioral effects)

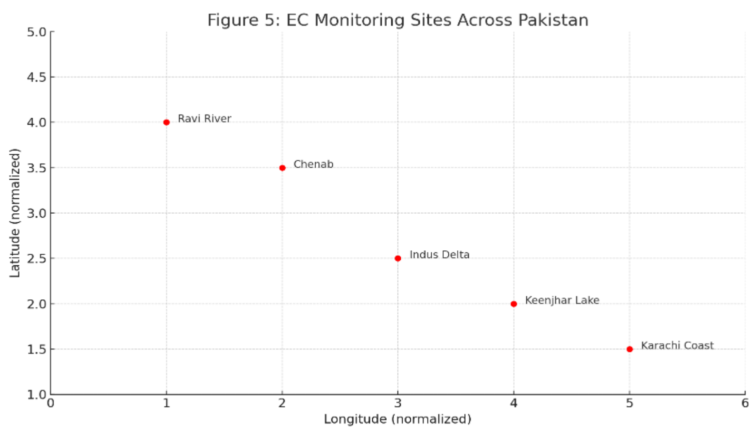

Figure 5: Map – EC Monitoring Sites Across Pakistan (Ravi River, Chenab, Indus Delta, Keenjhar Lake, Karachi coast)

Summary:

Emerging contaminants represent a hidden yet potent threat to aquatic ecosystems, particularly in developing regions like Pakistan where regulatory and infrastructural limitations exist. Their ability to bioaccumulate, disrupt endocrine and reproductive systems, and transfer across trophic levels demands urgent toxicological scrutiny and long-term monitoring. This article emphasizes the need for modern analytical detection tools, ecological risk assessment frameworks, and sustainable wastewater treatment technologies. Policymakers, researchers, and environmental agencies must collaboratively establish guidelines and invest in public awareness to mitigate the long-term impacts of ECs on both aquatic life and human health.

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