Journal of Water Resource Engineering and Pollution Studies
Volume 10, Issue 3, September-December, 2025
ISSN: 3107-8419 (Online)

Emerging Contaminants in Aquatic Ecosystems: Understanding the Sources, Impacts, Challenges, And Future Perspectives for Sustainable Water Quality Management

Dr. Priyanka Sharma[1], Sandeep Kumar Patel[2]

Assistant Professor[1], Student[1]

Department of Civil Engineering

IIMT College of Engineering

***Email ID**: priyanka.sharma35@gmail.com[1], skpatel204@rediffmail.com[2]*

ABSTRACT

The presence of emerging contaminants (ECs) in aquatic ecosystems has become one of the most pressing global environmental issues of the 21st century. These contaminants include pharmaceuticals, personal care products, pesticides, microplastics, industrial chemicals, and endocrine-disrupting compounds that are not completely removed by conventional wastewater treatment systems. Their continuous discharge into rivers, lakes, and oceans poses potential risks to aquatic organisms, biodiversity, and even human health through bioaccumulation and trophic transfer. This paper discusses the sources, occurrence, and environmental behavior of emerging contaminants, explores their effects on aquatic ecosystems, reviews key findings from recent literature, and identifies the challenges and opportunities for monitoring and management. The study emphasizes the urgent need for advanced analytical methods, effective policy frameworks, and sustainable remediation technologies to safeguard aquatic environments from the growing threat of emerging pollutants.

KEYWORDS: *Emerging Contaminants, Aquatic Ecosystems, Pharmaceuticals, Endocrine Disruptors, Microplastics, Water Pollution, Ecotoxicology, Wastewater Treatment.*

INTRODUCTION

Water is a fundamental resource for all life forms, yet its quality is increasingly threatened by a complex array of pollutants. Traditionally, water pollution studies have focused on conventional contaminants such as nutrients, heavy metals, and organic matter. However, in recent decades, attention has shifted toward a new category of pollutants known as emerging contaminants (ECs). These substances, though present in trace concentrations (often in nanograms or micrograms per liter), can have profound ecological and health implications due to their persistence, bioaccumulative nature, and biological activity.

Emerging contaminants are not yet regulated under most water quality standards, which complicates their detection, monitoring, and management. The proliferation of pharmaceuticals, industrial chemicals, and personal care products in daily life has resulted in their unintentional release into the environment through municipal wastewater, industrial effluents, and agricultural runoff. Aquatic ecosystems act as final sinks for these pollutants, where they interact with biotic and abiotic components, altering ecosystem balance and function. Understanding the dynamics of these contaminants is vital for developing effective mitigation and policy strategies for sustainable water resource management.

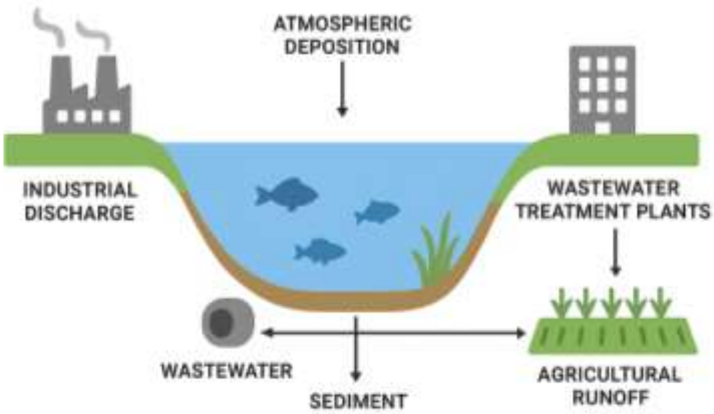

Figure 1: Conceptual Diagram of Emerging Contaminant Pathways in Aquatic Ecosystems

LITERATURE REVIEW

Historical Emergence of Concern

The recognition of emerging contaminants as significant environmental pollutants began in the late 1990s when advances in analytical chemistry allowed the detection of trace-level

Journal of Water Resource Engineering and Pollution Studies
Volume 10, Issue 3, September-December, 2025
ISSN: 3107-8419 (Online)

compounds in water bodies. Early studies identified pharmaceuticals and endocrine-disrupting chemicals as major contributors to aquatic contamination. Subsequent research expanded this list to include flame retardants, per- and polyfluoroalkyl substances (PFAS), nanomaterials, and microplastics.

Pharmaceuticals and Personal Care Products (PPCPs)

Pharmaceuticals enter aquatic systems primarily through domestic sewage and hospital wastewater. Drugs such as antibiotics, antidepressants, and hormones are often only partially metabolized by humans and animals, leading to their presence in effluents. Personal care products, including sunscreens, fragrances, and preservatives, also contribute to contamination. These substances can disrupt the endocrine system of aquatic organisms, cause behavioral changes, and affect reproduction.

Endocrine Disrupting Chemicals (EDCs)

EDCs interfere with hormonal signaling in aquatic organisms. Compounds such as bisphenol A (BPA), nonylphenol, and synthetic estrogens have been found to induce feminization in fish species and disrupt reproduction cycles. Their persistence and bioaccumulation potential make them particularly harmful over long exposure periods.

Microplastics and Nanoparticles

Microplastics have emerged as another significant category of emerging contaminants. These small plastic fragments, fibers, and beads originate from plastic degradation, textile fibers, and personal care products. They can act as carriers for toxic chemicals, absorb heavy metals, and physically damage aquatic organisms when ingested. Nanoparticles, including titanium dioxide and silver nanoparticles, are widely used in consumer products and can cause oxidative stress and cellular damage in aquatic species.

Per- and Polyfluoroalkyl Substances (PFAS)

PFAS are synthetic chemicals known for their water and oil repellency. Due to their chemical stability, they persist in the environment and bioaccumulate in aquatic food webs. Exposure to PFAS has been linked to immunotoxicity, hormonal imbalance, and developmental disorders in wildlife and humans.

Journal of Water Resource Engineering and Pollution Studies
Volume 10, Issue 3, September-December, 2025
ISSN: 3107-8419 (Online)

SOURCES OF EMERGING CONTAMINANTS

Table 1: Major Categories of Emerging Contaminants and Their Sources

Category	Common Examples	Primary Sources	Environmental Concern
Pharmaceuticals	Antibiotics, painkillers, antidepressants	Domestic sewage, hospitals	Antibiotic resistance, hormonal disruption
Personal Care Products	Fragrances, sunscreens, cosmetics	Household wastewater, urban runoff	Endocrine disruption, bioaccumulation
Industrial Chemicals	PFAS, flame retardants, surfactants	Manufacturing effluents, landfills	Persistence, toxicity
Agricultural Chemicals	Pesticides, fertilizers, veterinary drugs	Farm runoff, soil leaching	Aquatic toxicity, eutrophication
Microplastics & Nanoparticles	Plastic beads, fibers, TiO_2 nanoparticles	Plastic waste, cosmetics, textiles	Physical damage, carrier for toxins

Domestic and Municipal Wastewater

The primary source of emerging contaminants is domestic sewage, which contains residues from pharmaceuticals, detergents, and personal care products. Wastewater treatment plants are not designed to remove these complex organic compounds completely, resulting in their release into surface waters.

Industrial Effluents

Industrial processes contribute a wide range of contaminants, including solvents, surfactants, and synthetic chemicals. Textile, pharmaceutical, and chemical manufacturing industries are particularly notable contributors.

Agricultural Runoff

The use of veterinary drugs, pesticides, and fertilizers introduces contaminants into nearby streams and groundwater. These pollutants can persist in soil and enter aquatic systems through leaching and runoff.

Leachates from Landfills

Landfills containing discarded electronics, plastics, and medical waste serve as long-term sources of emerging contaminants, releasing them slowly into groundwater and surface water.

IMPACTS ON AQUATIC ECOSYSTEMS

Table 2: Effects of Emerging Contaminants on Aquatic Organisms

Contaminant Type	Affected Species	Observed Effects	Trophic Level Impact
Endocrine Disruptors	Fish, amphibians	Reproductive abnormalities, feminization	Population decline
Pharmaceuticals	Fish, algae, crustaceans	Behavioral changes, growth inhibition	Community imbalance
Antibiotics	Aquatic bacteria	Antibiotic resistance, loss of microbial diversity	Food web alteration
Microplastics	Zooplankton, shellfish	Gut blockage, reduced feeding	Bioaccumulation in higher predators

Ecotoxicological Effects

Even at trace concentrations, emerging contaminants can cause toxic effects on aquatic organisms. Pharmaceuticals such as antidepressants and antibiotics alter fish behavior and microbial communities, while endocrine disruptors affect reproduction and growth.

Bioaccumulation and Biomagnification

Certain contaminants, especially PFAS and hydrophobic organic compounds, accumulate in aquatic organisms and move up the food chain, posing risks to higher trophic levels, including humans.

Alteration of Microbial Communities

Antibiotic residues can lead to the development of antibiotic-resistant bacteria in aquatic ecosystems, posing a serious public health challenge.

Physical and Chemical Stress

Microplastics not only introduce toxic additives but also cause physical harm to aquatic species, leading to gut obstruction and reduced nutrient absorption.

CHALLENGES IN DETECTION AND MONITORING

Analytical Limitations

Detecting emerging contaminants at extremely low concentrations requires sophisticated instruments such as LC–MS/MS and GC–MS. However, many laboratories in developing regions lack such facilities, leading to underreporting of contamination levels.

Lack of Standardized Protocols

There are no universal guidelines or standardized protocols for sampling, analysis, and reporting of emerging contaminants, which hampers data comparability across studies.

Regulatory Gaps

Most emerging contaminants are not covered by existing environmental regulations. The absence of threshold limits for many compounds results in insufficient enforcement and control.

Complex Mixtures and Unknown Effects

Aquatic organisms are often exposed to mixtures of contaminants rather than single substances. The combined or synergistic effects of these mixtures are not well understood and remain an area of active research.

REMEDIATION AND TREATMENT TECHNOLOGIES

The removal of emerging contaminants (ECs) from aquatic and terrestrial ecosystems requires a combination of advanced physicochemical and biological treatment strategies. Conventional wastewater treatment systems are often inadequate for completely eliminating persistent organic micropollutants such as pharmaceuticals, personal care products, and endocrine-disrupting compounds. Therefore, recent research has focused on integrating innovative remediation and treatment technologies that are both efficient and sustainable.

Table 3: Advanced Treatment Technologies for Removal of Emerging Contaminants

Treatment Method	Mechanism	Effectiveness	Limitations
Advanced Oxidation Processes (AOPs)	Generation of hydroxyl radicals to degrade organic pollutants	High	High energy cost, by-product formation
Membrane Filtration (RO, NF)	Physical separation based on molecular size	Very High	Expensive, membrane fouling
Bioremediation	Microbial degradation of contaminants	Moderate to High	Dependent on microbial adaptation
Constructed Wetlands	Phytoremediation and natural microbial action	Moderate	Space requirement, slower rate

1. Advanced Oxidation Processes (AOPs)

Advanced Oxidation Processes are among the most promising technologies for degrading recalcitrant and non-biodegradable organic contaminants. AOPs function through the in-situ generation of highly reactive species, primarily hydroxyl radicals (•OH), which possess high oxidation potential and can mineralize complex pollutants into CO_2, H_2O, and inorganic ions.

- **Ozonation:** Ozone (O_3) oxidizes organic compounds directly or indirectly via radical pathways. It is highly effective for pharmaceuticals, pesticides, and dyes but requires precise control to minimize bromate formation.

- **Photocatalysis:** Semiconductor materials such as TiO_2, ZnO, and g-C_3N_4 are used under UV or visible light to catalyze pollutant degradation. The process's efficiency depends on light intensity, catalyst surface area, and pollutant concentration.

- **Fenton and Photo-Fenton Reactions:** These reactions use hydrogen peroxide (H_2O_2) and ferrous ions (Fe^{2+}) to generate radicals. The Photo-Fenton process, activated by UV or solar light, enhances radical production and degradation rates, making it viable for large-scale wastewater treatment.
- El**ectrochemical and Sonochemical AOPs:** These hybrid methods combine oxidation with electric current or ultrasonic energy to improve degradation kinetics and reduce by-product formation.

Journal of Water Resource Engineering and Pollution Studies
Volume 10, Issue 3, September-December, 2025
ISSN: 3107-8419 (Online)

AOPs are particularly effective as tertiary or polishing steps after biological treatment, ensuring near-complete elimination of trace-level pollutants.

2. Membrane Filtration Technologies

Pressure-driven membrane processes—such as microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO)—play a vital role in physically separating contaminants from water. The selectivity of each process depends on pore size and membrane material properties.

- **Nanofiltration (NF):** Effective in removing pharmaceuticals, heavy metals, and endocrine disruptors due to its intermediate pore size (0.001–0.01 µm).

- **Reverse Osmosis (RO):** Provides the highest removal efficiency for dissolved organic and inorganic species but is energy-intensive and susceptible to membrane fouling.

- **Hybrid Membrane Systems:** Integration with AOPs or biological treatments can mitigate fouling and extend membrane life while improving removal efficiency.

- **Emerging Trends:** The use of graphene oxide membranes, bio-inspired membranes, and membrane distillation systems are being explored for enhanced selectivity, lower fouling, and reduced operational costs.

While membrane technologies are highly effective, ongoing research focuses on energy-efficient operation, fouling control, and recycling of concentrate waste.

3. Constructed Wetlands and Phytoremediation

Nature-based solutions, such as constructed wetlands (CWs) and phytoremediation, mimic natural purification processes. They are eco-friendly, cost-effective, and sustainable options for decentralized wastewater treatment, especially in rural and peri-urban areas.

- **Constructed Wetlands (CWs):** Utilize the synergistic action of plants, microorganisms, and substrates (such as gravel or sand) to remove pollutants through adsorption, filtration, and microbial degradation. Vertical flow CWs enhance oxygen transfer, while horizontal flow CWs are better for anaerobic degradation.

- **Phytoremediation:** Certain plants, such as *Phragmites australis*, *Typha latifolia*, and *Eichhornia crassipes*, can absorb, accumulate, or transform organic and inorganic contaminants.

- **Rhizodegradation:** Microbial communities in the rhizosphere break down contaminants, supported by plant root exudates that enhance microbial metabolism.

Recent developments include genetically modified plants and engineered wetlands that exhibit improved pollutant uptake and resilience under variable environmental conditions.

4. Bioremediation

Bioremediation leverages the metabolic capabilities of microorganisms—such as bacteria, fungi, and algae—to degrade, transform, or immobilize contaminants in soil and water. It offers a sustainable and low-cost approach to removing organic pollutants.

- **Microbial Degradation:** Species such as *Pseudomonas putida*, *Bacillus subtilis*, and *Aspergillus niger* can degrade pharmaceuticals, dyes, and hydrocarbons.

- **Bioaugmentation and Biostimulation:** These strategies involve adding specific microbial strains or nutrients to enhance biodegradation rates.

- **Enzymatic Bioremediation:** Isolated enzymes (e.g., laccases, peroxidases) are being employed for targeted degradation of phenolic compounds and endocrine disruptors.

- **Algal Bioremediation:** Microalgae can simultaneously remove nutrients and contaminants while generating valuable biomass for bioenergy applications.

Advances in metagenomics, genetic engineering, and synthetic biology are enabling the design of custom microbial consortia capable of degrading complex mixtures of emerging contaminants.

5. Integrated and Hybrid Treatment Systems

The future of remediation lies in integrated treatment systems that combine the strengths of multiple technologies. For instance:

- AOP-biological hybrid systems enhance overall efficiency by breaking down complex pollutants into biodegradable intermediates.

- Membrane-bioreactor (MBR) systems combine biological treatment with physical separation for superior effluent quality.

- Wetland–AOP or Photocatalytic–Bioreactor systems offer sustainable solutions for large-scale municipal and industrial applications.

SCOPE AND FUTURE PERSPECTIVES

Policy Development and Regulation

Developing nations need to adopt regulatory frameworks for monitoring and managing emerging contaminants. The inclusion of ECs in national water quality standards will ensure stricter control and accountability.

Public Awareness and Behavioral Change

Improper disposal of pharmaceuticals and plastics is a major source of contamination. Awareness campaigns and take-back programs can reduce the entry of pollutants into wastewater systems.

Research and Innovation

Continuous research into detection techniques, ecotoxicological assessment, and cost-effective treatment methods is essential. The integration of artificial intelligence and big data analytics can improve monitoring and predictive modeling of contaminant behavior.

Sustainable Industrial Practices

Industries must adopt green chemistry principles, minimize chemical use, and recycle wastewater to reduce the introduction of new contaminants.

Interdisciplinary Collaboration

Effective management of emerging contaminants requires collaboration between environmental scientists, policymakers, engineers, and public health experts. Global cooperation is essential to address transboundary pollution in shared water bodies.

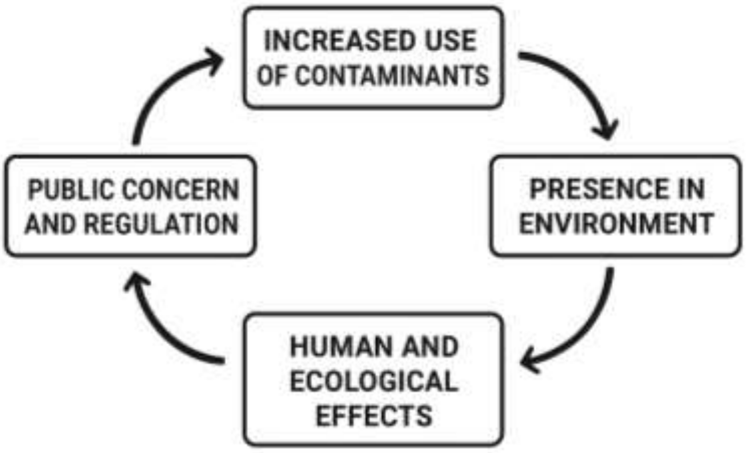

Figure 2: Global Concern and Impact Cycle of Emerging Contaminants

CONCLUSION

Emerging contaminants represent a significant and growing threat to aquatic ecosystems worldwide. Their complex nature, persistence, and biological activity challenge existing wastewater treatment and regulatory frameworks. As modern lifestyles continue to rely heavily on pharmaceuticals, plastics, and synthetic chemicals, the pressure on aquatic systems is expected to intensify. Addressing this issue requires a comprehensive and multidisciplinary approach that combines technological innovation, regulatory reform, public participation, and global cooperation. By improving monitoring systems, adopting sustainable technologies, and enforcing responsible waste management, societies can mitigate the adverse impacts of emerging contaminants and ensure the long-term health of aquatic ecosystems and the communities that depend on them.

REFERENCES

1. Ahmed, M. B., Zhou, J. L., Ngo, H. H., & Guo, W. (2017). *Adsorptive removal of antibiotics from water and wastewater: Progress and challenges.* Science of the Total Environment, 532, 112–126.
2. Archer, E., Petrie, B., Kasprzyk-Hordern, B., & Wolfaardt, G. M. (2017). *The fate of pharmaceuticals and personal care products (PPCPs) during wastewater treatment and their impact on the aquatic environment.* Science of the Total Environment, 601–602, 1496–1512.
3. Bernhardt, E. S., Rosi, E. J., & Gessner, M. O. (2017). *Synthetic chemicals as agents of global change.* Frontiers in Ecology and the Environment, 15(2), 84–90.

4. Blair, B. D., Crago, J. P., Hedman, C. J., & Klaper, R. D. (2013). *Pharmaceuticals and personal care products found in the Great Lakes: Impact on aquatic life.* Environmental Pollution, 187, 5–14.
5. Boxall, A. B. A. (2012). *New and emerging water pollutants arising from agriculture.* OECD Publishing.
6. Daughton, C. G., & Ternes, T. A. (1999). *Pharmaceuticals and personal care products in the environment: Agents of subtle change?* Environmental Health Perspectives, 107(Suppl 6), 907–938.
7. Deblonde, T., Cossu-Leguille, C., & Hartemann, P. (2011). *Emerging pollutants in wastewater: A review of the literature.* International Journal of Hygiene and Environmental Health, 214(6), 442–448.
8. Ebele, A. J., Abdallah, M. A.-E., & Harrad, S. (2017). *Pharmaceuticals and personal care products (PPCPs) in the freshwater aquatic environment.* Emerging Contaminants, 3(1), 1–16.
9. Godfrey, L., & Oelofse, S. (2017). *Historical review of waste management and recycling in South Africa.* Resources, 6(4), 57.
10. González-Pleiter, M., Velázquez, D., & Leganés, F. (2020). *Microplastics as carriers of emerging contaminants: Environmental implications.* Environmental Pollution, 257, 113356.