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Emerging Contaminants in Aquatic Ecosystems: Ecotoxicological Impacts, Human Health Risks and Analytical Detection Approaches

[1]Prasannarao Marsakatla and [2]Dr. Shivendra Verma

[1]Research Scholar, YBN University Ranchi, Ulatu, Jharkhand, India
[2]Associate Professor, YBN University Ranchi, Ulatu, Jharkhand, India

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Corresponding Author: Prasannarao Marsakatla

Abstract

Emerging contaminants (ECs) have become a growing environmental concern due to their continuous release into aquatic ecosystems through domestic wastewater, industrial effluents, healthcare facilities, and agricultural runoff. These contaminants, including pharmaceuticals, antibiotics, endocrine-disrupting compounds, personal care products, pesticides, industrial chemicals, and microplastics, are frequently detected in surface and groundwater at trace concentrations. Despite their low levels, many ECs are persistent, biologically active, and capable of bioaccumulation, posing significant risks to aquatic ecosystems and human health. This paper examines the occurrence, classification, and ecotoxicological impacts of emerging contaminants, emphasizing their adverse effects on aquatic organisms, such as endocrine disruption, reproductive abnormalities, oxidative stress, antimicrobial resistance, and biodiversity loss. It also highlights the role of physicochemical parameters, including pH, temperature, dissolved oxygen, biological oxygen demand, chemical oxygen demand, electrical conductivity, and total dissolved solids, in influencing the transport, persistence, and transformation of these contaminants in aquatic environments. Furthermore, the paper discusses advanced analytical techniques, including High-Performance Liquid Chromatography (HPLC), Liquid Chromatography-Tandem Mass Spectrometry (LC-MS/MS), Gas Chromatography-Mass Spectrometry (GC-MS), Fourier Transform Infrared Spectroscopy (FTIR), Raman Spectroscopy, and Inductively Coupled Plasma-Mass Spectrometry (ICP-MS), for accurate detection and monitoring of ECs. The study underscores the need for effective monitoring, improved wastewater treatment, and sustainable management strategies to safeguard water quality, aquatic biodiversity, and public health.

Keywords: Emerging contaminants, ecotoxicology, aquatic ecosystems, pharmaceuticals, microplastics, water pollution, analytical techniques

Introduction

Water resources are fundamental to sustaining ecological integrity, economic development, agricultural productivity, and public health. However, increasing anthropogenic activities have significantly altered the quality of freshwater resources worldwide. Rapid industrialization, urban expansion, population growth, intensive agricultural practices, pharmaceutical consumption, and improper disposal of domestic and industrial wastes have introduced numerous chemical pollutants into aquatic environments. While conventional pollutants such as nutrients, heavy metals, and organic matter have long been monitored and regulated, increasing scientific attention has recently focused on a diverse group of pollutants collectively known as emerging contaminants (ECs) or contaminants of emerging concern (CECs). These substances have become one of the most pressing environmental issues because of their widespread occurrence, environmental persistence, and potential adverse effects on both ecosystems and human health.

Emerging contaminants include pharmaceuticals, antibiotics, personal care products, endocrine-disrupting compounds, pesticides, industrial chemicals, microplastics, nanomaterials, and other biologically active substances that are continuously introduced into aquatic ecosystems through municipal wastewater, hospital effluents, industrial discharges, agricultural runoff, landfill leachates, and urban stormwater. Unlike conventional pollutants, these compounds are often detected at extremely low concentrations, ranging from nanograms per litre (ng/L) to micrograms per litre (µg/L). Nevertheless, their continuous release, persistence, bioaccumulation potential, and complex mixture effects enable them to produce chronic ecological impacts even at trace levels. Conventional wastewater treatment systems are frequently ineffective in completely removing these contaminants, resulting in their continuous circulation through surface water, groundwater, sediments, and drinking water sources.

The ecological implications of emerging contaminants extend beyond individual organisms to affect entire aquatic ecosystems. Numerous studies have demonstrated that prolonged exposure to pharmaceuticals, antibiotics, endocrine disruptors, and microplastics can cause endocrine disruption, reproductive impairment, developmental abnormalities, oxidative stress, behavioural alterations, immunotoxicity, antimicrobial resistance, and biodiversity decline. These contaminants also pose significant human health concerns through long-term exposure via drinking water and food chains. Consequently, environmental monitoring has evolved from measuring chemical concentrations alone to integrating ecotoxicological assessment and ecological risk evaluation.

Considering these challenges, there is an increasing need for comprehensive understanding of the sources, classification, environmental behaviour, ecotoxicological effects, human health implications, and advanced analytical methods used for detecting emerging contaminants. This review therefore synthesizes current knowledge regarding major classes of emerging contaminants, their environmental occurrence, ecological and health impacts, physicochemical factors influencing their transport and persistence, and modern analytical techniques employed for their detection. The review also emphasizes the importance of integrated monitoring programmes, improved wastewater treatment technologies, and evidence-based environmental management strategies to support sustainable water resource protection and pollution control.

Emerging Contaminants (ECS)

Emerging contaminants (ECs), also referred to as Contaminants of Emerging Concern (CECs), represent a diverse group of naturally occurring and synthetic chemical substances that have gained considerable scientific, regulatory, and environmental attention over the past two decades due to their increasing occurrence in aquatic ecosystems and their potential adverse effects on human health and ecological integrity. Unlike conventional pollutants, emerging contaminants are generally not included in routine environmental monitoring programmes, nor are they comprehensively regulated under existing water quality legislation. However, advancements in analytical chemistry have enabled the detection of these contaminants at trace concentrations, revealing their widespread presence in rivers, lakes, groundwater, drinking water, wastewater, sediments, soils, and even atmospheric environments (Sauvé & Desrosiers, 2014) [16].

The term "emerging" does not necessarily imply that these contaminants are newly introduced into the environment. Rather, it refers to chemicals whose occurrence, persistence, ecological significance, toxicological impacts, or environmental behaviour has only recently become recognized due to improvements in scientific understanding and analytical methodologies. Many emerging contaminants have been used commercially for several decades but remained undetected because conventional analytical instruments lacked sufficient sensitivity for trace-level detection.

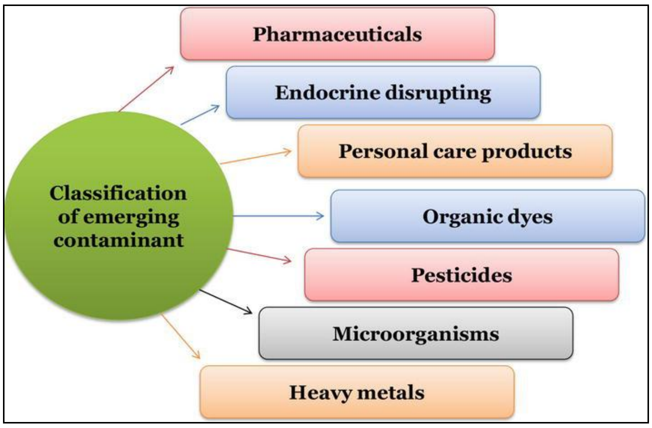

Fig 1: Emerging contaminants

Growing concerns regarding emerging contaminants stem from their continuous introduction into aquatic ecosystems through domestic wastewater, industrial effluents, agricultural runoff, healthcare facilities, landfill leachate, and urban stormwater. Many of these substances are biologically active, environmentally persistent, resistant to conventional wastewater treatment, and capable of inducing chronic toxicity even at concentrations measured in nanograms per litre (ng/L) or micrograms per litre (µg/L). Their continuous discharge into freshwater ecosystems has transformed them into one of the most significant environmental challenges confronting modern water quality management.

Unlike conventional pollutants, whose environmental effects generally become evident at relatively high concentrations, emerging contaminants frequently produce subtle but biologically significant impacts following long-term exposure. These impacts include endocrine disruption, reproductive abnormalities, behavioural alterations, developmental defects, antimicrobial resistance, immunotoxicity, genotoxicity, neurotoxicity, oxidative stress, biodiversity loss, and ecological imbalance. Consequently, environmental monitoring programmes have increasingly shifted from merely assessing chemical concentrations towards evaluating biological responses and ecological risks associated with contaminant exposure.

Modern environmental science therefore considers emerging contaminants as priority pollutants requiring interdisciplinary investigation involving environmental chemistry, ecotoxicology, hydrogeology, microbiology, analytical chemistry, toxicology, geographical information systems, and environmental risk assessment. Such integrated approaches enable comprehensive understanding of contaminant occurrence, transport mechanisms, ecological impacts, and potential mitigation strategies.

Definition of Emerging Contaminants

Emerging contaminants are chemical, biological, or particulate substances that are increasingly detected in the environment and are suspected to pose risks to ecosystems and human health but are not yet comprehensively regulated under existing environmental legislation.

According to Sauvé and Desrosiers (2014) [16], emerging contaminants include substances that have either recently been introduced into the environment or whose environmental occurrence and ecological significance have only recently become recognized through scientific investigation.

The United States Environmental Protection Agency (USEPA) defines contaminants of emerging concern as chemicals or microorganisms that are not routinely monitored but possess the potential to enter aquatic environments and produce ecological or human health impacts.

Similarly, the World Health Organization (WHO) considers emerging contaminants to include pharmaceuticals, endocrine-disrupting chemicals, industrial compounds, pesticides, antibiotics, and other substances that require increased environmental surveillance due to their persistence and biological activity.

Characteristics of Emerging Contaminants

Emerging contaminants possess several distinctive characteristics that differentiate them from conventional pollutants.

a. Presence at Trace Concentrations
b. Continuous Environmental Input
c. Environmental Persistence
d. Biological Activity
e. Bioaccumulation
f. Resistance to Wastewater Treatment
g. Complex Mixture Effects

Classification of Emerging Contaminants

Emerging contaminants encompass a wide variety of chemical groups. Their classification is generally based upon source, chemical composition, and environmental behaviour.

1. Pharmaceuticals
2. Antibiotics
3. Personal Care Products (PPCPs)
4. Endocrine-Disrupting Compounds (EDCs)
5. Pesticides
6. Industrial Chemicals
7. Microplastics
8. Nanomaterials

Ecotoxicology

Ecotoxicology is an interdisciplinary branch of environmental science that studies the adverse effects of chemical, physical, and biological pollutants on living organisms and ecosystems. It integrates principles of ecology, toxicology, environmental chemistry, biology, and environmental risk assessment to understand how contaminants affect aquatic and terrestrial organisms at different levels of biological organization, including individuals, populations, communities, and ecosystems.

Unlike conventional toxicity studies, which primarily focus on human health, ecotoxicology evaluates the responses of non-target organisms such as algae, aquatic plants, zooplankton, benthic organisms, fish, amphibians, and microorganisms. These organisms often serve as bioindicators because they are highly sensitive to changes in environmental quality and contaminant exposure.

Emerging contaminants have become an important focus of ecotoxicological research due to their continuous release into aquatic environments and their persistence even at trace concentrations. Pharmaceuticals, antibiotics, endocrine-disrupting compounds, pesticides, and microplastics can interfere with normal physiological processes, causing reproductive abnormalities, endocrine disruption, oxidative stress, behavioural changes, growth inhibition, immune suppression, and reduced biodiversity. Long-term exposure to mixtures of contaminants may also alter ecosystem functioning and food-web dynamics.

Ecotoxicological assessment commonly involves laboratory toxicity tests, field investigations, bioindicator studies, and ecological risk assessment. Parameters such as mortality, growth, reproduction, enzyme activity, species diversity, and behavioural responses are used to evaluate contaminant effects. These assessments provide valuable information for identifying environmentally hazardous substances and establishing appropriate pollution control strategies.

Ecotoxicological Effects of Emerging Contaminants

Emerging contaminants have become a significant concern in ecotoxicology due to their continuous discharge into aquatic ecosystems and their potential to adversely affect aquatic organisms even at very low concentrations. Unlike conventional pollutants, many emerging contaminants are biologically active compounds that can interfere with physiological and biochemical processes in non-target organisms. Continuous exposure may result in chronic toxicity, reduced reproductive success, developmental abnormalities, endocrine disruption, and alterations in ecosystem structure and function.

Aquatic organisms such as algae, plankton, aquatic plants, fish, molluscs, crustaceans, amphibians, and benthic organisms are particularly vulnerable because they are continuously exposed to contaminants present in water and sediments. Pharmaceuticals and personal care products may alter the behaviour, metabolism, and growth of aquatic species, while antibiotics can disturb microbial communities and promote the development of antibiotic-resistant bacteria. Endocrine-disrupting compounds interfere with hormone regulation, causing reproductive disorders, feminization of fish, reduced fertility, and developmental defects.

Microplastics have emerged as another important ecotoxicological concern because they are readily ingested by aquatic organisms and may act as carriers for toxic chemicals, pathogens, and heavy metals. Their accumulation in aquatic food webs can lead to reduced feeding efficiency, tissue damage, oxidative stress, and impaired reproduction.

The ecotoxicological impacts of emerging contaminants are often enhanced due to mixture toxicity, where multiple contaminants coexist in the environment and produce additive or synergistic effects. Therefore, assessing ecological risks requires consideration of combined contaminant exposure rather than individual compounds alone.

Understanding these ecological effects is essential for developing effective environmental monitoring programmes and pollution control strategies aimed at protecting freshwater biodiversity and ecosystem health.

Human Health Impacts of Emerging Contaminants

Emerging contaminants have attracted increasing attention because of their potential implications for human health. Although these contaminants are generally detected at trace concentrations in water resources, continuous exposure through drinking water, food consumption, and environmental contact may lead to adverse health effects over time. Their persistence and biological activity make them a matter of concern for environmental and public health authorities worldwide.

Pharmaceutical residues and antibiotics present in water may contribute to the development of antimicrobial resistance, which has become one of the most serious global public health challenges. Continuous exposure to low concentrations of antibiotics can promote the growth of resistant microorganisms, reducing the effectiveness of life-saving medicines.

Endocrine-disrupting compounds such as bisphenol-A, phthalates, and certain pesticides may interfere with the human endocrine system by mimicking or blocking natural hormones. Long-term exposure has been associated with reproductive disorders, developmental abnormalities, thyroid dysfunction, metabolic disorders, and certain hormone-related cancers.

Microplastics are increasingly detected in drinking water, food products, and even human tissues. Although research is still evolving, concerns have been raised regarding their potential to cause inflammation, oxidative stress, cellular damage, and transport of toxic chemicals into the human body.

The degree of health risk depends on contaminant concentration, duration of exposure, age, physiological condition, and the combined effects of multiple contaminants. Therefore, continuous monitoring, improved wastewater treatment, safe disposal of pharmaceuticals, and public awareness are essential for minimizing human exposure and protecting public health.

Physicochemical Parameters Affecting Emerging Contaminants

The occurrence, transport, transformation, and persistence of emerging contaminants in aquatic environments are strongly influenced by the physicochemical characteristics of water. These parameters determine contaminant mobility, degradation, bioavailability, and ecological behaviour. Consequently, assessment of physicochemical water quality is an essential component of studies investigating emerging contaminants.

Among the most important parameters, pH influences the ionization and solubility of many pharmaceuticals and industrial chemicals, thereby affecting their mobility and adsorption onto sediments. Temperature regulates chemical reaction rates, microbial activity, and degradation processes, while dissolved oxygen (DO) reflects the oxygen status of aquatic ecosystems and influences aerobic biodegradation of contaminants.

Biological Oxygen Demand (BOD) and Chemical Oxygen Demand (COD) provide information on the organic pollution load and indirectly indicate the presence of wastewater-derived contaminants. Elevated BOD and COD values often suggest increased inputs of municipal sewage or industrial effluents, which are important sources of emerging contaminants.

Electrical Conductivity (EC) and Total Dissolved Solids (TDS) indicate the concentration of dissolved ions and are useful for assessing changes in water chemistry resulting from industrial discharge, agricultural runoff, and wastewater inputs. Turbidity affects light penetration and influences photodegradation processes, whereas Total Suspended Solids (TSS) provide surfaces for adsorption and transport of hydrophobic contaminants.

Nutrients such as nitrate and phosphate also influence aquatic productivity and microbial activity, indirectly affecting contaminant degradation. Therefore, comprehensive physicochemical analysis provides valuable background information for interpreting the occurrence and environmental behaviour of emerging contaminants.

Table 1: Major Physicochemical Parameters and Their Significance

Parameter	Significance in Emerging Contaminant Studies
pH	Controls ionization and solubility of contaminants
Temperature	Influences degradation and microbial activity
Dissolved Oxygen (DO)	Indicates aerobic conditions and biodegradation potential
Biological Oxygen Demand (BOD)	Reflects biodegradable organic pollution
Chemical Oxygen Demand (COD)	Indicates total oxidizable pollutants
Electrical Conductivity (EC)	Measures dissolved ionic content
Total Dissolved Solids (TDS)	Indicates dissolved inorganic and organic substances
Turbidity	Influences light penetration and photodegradation
Total Suspended Solids (TSS)	Provides adsorption sites for contaminants
Nitrate & Phosphate	Affect microbial activity and ecosystem productivity

Detection Techniques for Emerging Contaminants

The accurate detection and quantification of emerging contaminants require advanced analytical techniques because these substances are generally present at trace concentrations ranging from nanograms per litre (ng/L) to micrograms per litre (µg/L). Conventional water quality analysis methods are often inadequate for identifying these contaminants due to their low concentrations and complex chemical structures. Therefore, modern analytical instruments with high sensitivity and selectivity are widely employed in environmental monitoring.

Among the most commonly used techniques, High-Performance Liquid Chromatography (HPLC) is extensively applied for the analysis of pharmaceuticals, antibiotics, and personal care products. Liquid Chromatography coupled with Tandem Mass Spectrometry (LC-MS/MS) is regarded as one of the most reliable techniques because it provides high sensitivity, accuracy, and the capability to detect multiple contaminants simultaneously. Similarly, Gas Chromatography-Mass Spectrometry (GC-MS) is suitable for volatile and semi-volatile organic compounds, including pesticides and industrial chemicals.

Spectroscopic techniques such as Fourier Transform

Infrared Spectroscopy (FTIR) and Raman Spectroscopy are widely used for identifying and characterizing microplastics based on their polymer composition. In addition, Ultraviolet-Visible (UV-Vis) Spectrophotometry is frequently used for routine analysis of physicochemical parameters, while Inductively Coupled Plasma-Mass Spectrometry (ICP-MS) is employed for determining trace metals associated with emerging contaminant studies.

Selection of an appropriate analytical technique depends on the type of contaminant, required detection limits, sample matrix, analytical cost, and available laboratory facilities. The combination of chromatographic and spectrometric techniques has significantly improved the reliability of environmental monitoring programmes and has enabled researchers to detect contaminants at extremely low concentrations.

Conclusion

Emerging contaminants have become one of the most significant environmental concerns affecting aquatic ecosystems worldwide. Although generally present at trace concentrations, their continuous discharge, persistence, biological activity, and resistance to conventional wastewater treatment processes have resulted in widespread contamination of surface water, groundwater, sediments, and even drinking water resources. Pharmaceuticals, antibiotics, endocrine-disrupting compounds, pesticides, industrial chemicals, microplastics, and nanomaterials collectively represent a diverse group of contaminants capable of producing long-term ecological and human health impacts through bioaccumulation, chronic toxicity, endocrine disruption, oxidative stress, antimicrobial resistance, and alterations in ecosystem structure and function.

The study highlights that the environmental behaviour of emerging contaminants is strongly influenced by physicochemical characteristics of aquatic systems, including pH, temperature, dissolved oxygen, organic matter, conductivity, nutrient levels, and suspended solids, which regulate contaminant mobility, transformation, persistence, and bioavailability. Understanding these interactions is essential for accurate ecological risk assessment and effective environmental management.

Recent advances in analytical techniques, particularly LC-MS/MS, GC-MS, HPLC, FTIR, Raman spectroscopy, and ICP-MS, have substantially improved the detection and quantification of contaminants at extremely low concentrations, enabling more reliable environmental monitoring. However, challenges remain due to mixture toxicity, limited regulatory standards, inadequate wastewater treatment infrastructure, and insufficient long-term monitoring programmes, especially in developing countries.

Future research should prioritize integrated monitoring of multiple contaminant classes, evaluation of combined toxicity effects, development of cost-effective treatment technologies, incorporation of ecotoxicological biomarkers into routine monitoring programmes, and strengthening of environmental regulations. Collaborative efforts involving researchers, policymakers, environmental agencies, healthcare sectors, and industries are essential for minimizing contaminant release and safeguarding water resources. A multidisciplinary and sustainable approach will be critical for protecting aquatic biodiversity, ensuring water quality, and reducing long-term risks to human health in the face of increasing environmental pressures.

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