



(REVIEW ARTICLE)



Emerging pollutants in water and their remediation techniques with special emphasis on bioremediation: A review

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Abstract

Fresh water is the primary requirement for sustaining life on earth. Availability and access to safe drinking water is of greatest importance to maintain a healthy life. Extensive growth in industrialization and urbanization has led to increased pollution of natural water bodies with inorganic and organic pollutants and has become one of the greatest challenges of modern age. Emerging pollutants, both organic and inorganic, are chemicals which have major chronic and acute toxicity impacts on both flora and fauna and above a certain limit can affect human health as well. There are different types of these pollutants present in water bodies and due to their persistent nature are categorized as persistent inorganic (such as heavy metals) and organic (such as, pharmaceuticals, pesticides, endocrine disrupting agents, personal care products, etc.) pollutants and pose a serious problem at global level. This literature review aims to discuss these chemicals of concern with their sources, fate and health impacts and provides insight at the current challenges posed by the presence of emerging pollutants in the aquatic environment. Many researchers have designed and progressed in different remediation techniques of such chemicals, but these are all very diverse in nature. These processes include bioremediation, phyto-remediation, use of sorbents, use of membranes, activation of sludge, advanced oxidation method etc. This review intends to emphasize on bioremediation, as it is the most sustainable technique and most suitable to achieve sustainable environment.

Keywords: Aquatic Environment; Persistent Pollutants; Toxicity; Bioremediation Technique; Sustainable Environment

1. Introduction

Increasing pollution in the environment has become one of the most challenging global issues. Continuous urbanization, industrialization and increased deforestation have contributed to major pollution concerns.[1] Different categories of pollutants can be found in the environment. Improperly treated industrial effluents containing heavy metals, harmful chemicals, and pharmaceuticals, pesticides directly from agricultural areas, personal care products, home and cloth cleaning products are some of the continuous sources of pollutants in environment.[2] These chemicals are mostly persistent in nature, prone to bio-accumulation and are called persistent organic and inorganic pollutants. These chemicals act as endocrine disruptors and after a certain level affects human health.[3]

Water is the most essential resource for sustaining life on earth, but it has become one of the most vulnerable ecological components due to increasing presence of pollutants in natural water bodies. In the third World Water Forum, held in Kyoto, Japan in 2002, it was discussed that every day around 2 million tons of different types of pollutants were being discharged into various water bodies around the earth. This quantity was almost equal to the weight of terrestrial pollutants.[4,5] This literature review aims to discuss these chemicals of concern with their sources, fate and insight into the current challenges posed by the presence of emerging pollutants in the aquatic environment and also human health

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impacts. It also intends to summarize some of the remediation techniques to give an easy understanding of the methods which can be applied to achieve sustainable environment.

After thoroughly going through some of the existing literature, it is evident that these pollutants in aquatic environment can be characterized by their physical and chemical nature which even changes over time. These chemicals have the ability to get incorporated into food chain and bio-accumulate in the living organisms and ultimately affect human beings. Modern detection techniques have led to identification of newer and increased number of pollutants and their derivatives in water. [6,7]. These components are referred to as emerging pollutants. Emerging pollutants include industrial effluents, every day household products, and pharmaceutical wastes, products from anthropogenic sources like personal care products, surfactants, phthalates, plastics and plasticizers. Literature studies reveal that these products require additional surveillance because of their persistent nature and their toxic effects on aquatic flora, fauna and human beings as well [4, 8]. But the cost of monitoring these chemicals is very high which limits the progress. So, establishing a proper database about properties, derivatives and the toxicological effects of these emerging pollutants still remains an issue. [9]

2. Emerging Pollutants in Water Environment

In the early 1800s, the first emerging pollutants were discovered in aquatic bodies. [10]. These pollutants are the results of uncontrolled deposition of waste materials which are not properly monitored and ultimately affect the environment adversely. There are more than 700 compounds grouped in 20 classes of emerging pollutants, such as “surfactants, antibiotics, pharmaceuticals, steroid hormones, some endocrine-disrupting compounds (EDCs), fire retardants, sunscreens, disinfection by-products, new pesticides and pesticide metabolites, naturally-occurring algal toxins”, etc. [11]. Some of these emerging pollutants have existed in the environment for several years, but only recently their qualitative and quantitative analysis has been done. As their quantity has been rising every day, they might be hazardous for ecosystems. [12]

Endocrine disrupting chemicals are the most explored chemicals as they are already known to affect the endocrine system of animals on chronic exposure. More than 200 of these compounds have been identified and many of these are regularly monitored. Pharmaceuticals, flame retardants and personal care products are also among the most commonly researched pollutants. Currently, more than 3 million tons of phthalates compounds are being produced world-wide, which is used as plasticizers in plastics and as fixing agents in cosmetics. But many these pollutants are not subjected to regulations or standardization because of very few information available on the effects of chronic exposure of these chemicals. [14, 15].

3. Sources of emerging pollutants in the environment

There are many point sources as well as diffused sources of emerging chemicals in environment. Sources of these chemicals and their metabolites are mostly anthropogenic and released into environment from various ways such as industrial effluents, households, hospitals, washed away from agricultural lands and landfills. [14,15]. Persistence of these compounds in nature largely depends on their properties, volatility, polarity and exposure to natural causes like wind, UV rays, hydrolysis, photolysis and microbial degradation. Some of the metabolites pose higher level of toxicity than the parent compounds [4].

One of the most concerning compound among the emerging pollutants is the pharmaceutical compounds. Pharmaceuticals have gathered huge interest among researchers due their diverse physical and biochemical nature. These compounds include synthetic hormones that are mostly steroid in nature, anti-inflammatory drugs, anti-depressants, antibiotics, anti-hypertensive drugs and anti-epileptic drugs. [16] After administration, these compounds and their metabolites are excreted and are found in hospital effluents, sewers and surface water bodies. [17, 18] Studies have shown that antibiotics present in some rivers around the world have exceeded the safe level by 300 times. According to WHO, the biggest threat to global health and development is antibiotic resistance, as antibiotics have become less effective against infectious diseases due to environmental pollution caused by persistent pollutants. [19, 20].

The next compound of interest in the emerging pollutants category is the organic UV filters. Organic UV filters are extensively used in personal care products such as sunscreens. Most sunscreen products include ethylhexyl methoxycinnamate, octocrylene, butyl methoxydibenzoyl methane, and benzophenone-3, etc. due to their UVA and UVB absorption properties and ability to protect the user from solar radiation related damages. They also increase light stability cosmetics like skin cream and lotions, hair dyes and hair sprays, shampoos etc. These compounds enter water

bodies mostly from household sources. It is easily absorbed in human skin, as well as can penetrate other living organisms in environment due to their lipophilic nature. Some studies have highlighted their endocrine disrupting nature and their ability to bio-accumulate. [18, 19]

Some other compounds under scrutiny as emerging pollutants are water disinfectant by-products, flame retardants, manufactured nonmaterial, polybrominated and polyfluorinated compounds and fuel additives. [20]

So, the major sources of emerging pollutants include

- Incompletely removed chemicals from wastewater treatment plants which are disposed into large water bodies like rivers and seas.
- Agricultural land and other surfaces, like landfills, ran off water get naturally transported into water streams.

One the most concerning factor about the increase in emerging chemicals concentration in aquatic environment is climate change, which results into increased temperature and incidents of draught. Concentration of pollutants rises with declining water quality and volume.

Also desalination of sea water produces some by-products which are again disposed into the water.

Along with bio-accumulation, emerging pollutants are also deposited into the sediments of water bodies and are difficult to remove. Deposition of more emerging chemicals only give rise to the volume of these compounds already present in the water.

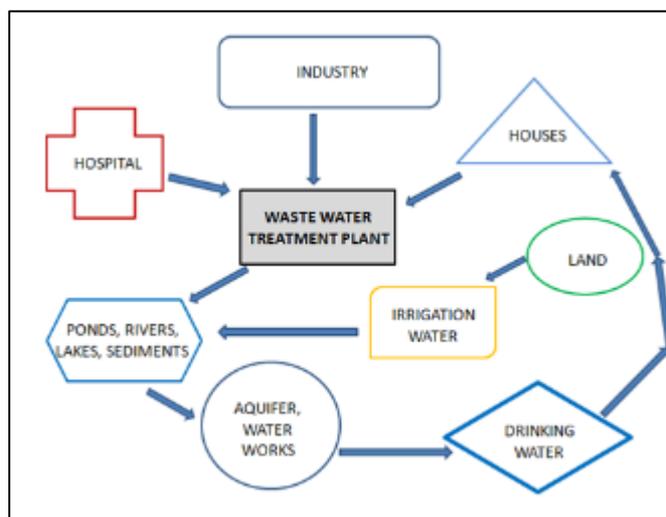


Figure 1 Sources of emmerging pollutnts in environment

3.1. Health and environmental risk factors of emerging chemicals:

Research works on emerging pollutants have established the toxic effects in very minute concentrations. These chemicals may disrupt aquatic organisms (reproduction, growth, behavior), promote antibiotic resistance, and present potential human-health risks through drinking water and food chains. Hormonal interference in fishes, cytotoxicity, genotoxicity, endocrine disruption and immune toxicity are few examples of toxic effects of these chemicals exhibited in natural and laboratory experiments. It is still difficult to establish chronic toxicity effects on human beings due to insufficient experiments and data. [21]

3.2. Remediation approaches applied for removal of emerging chemicals:

Remediation techniques can be grouped into:

- **Physical:** Adsorption of chemicals by activated carbon, ion-exchange resins, membrane filtration, sedimentation, flotation, etc are being used.
- **Chemical:** Advanced oxidation processes, coagulation, electrochemical oxidation are a few examples of chemical treatment.

- **Bioremediation:** In these process microorganisms, enzymes, plants, or whole ecosystems (e.g., constructed wetlands) are used to transform, degrade, or sequester emerging pollutants. Bioremediation is often the most sustainable option for long-term, large-scale treatment. [22, 23]

3.3. Mechanisms of bioremediation:

Bacteria from genera such as *Pseudomonas*, *Sphingomonas*, *Bacillus*, *Rhodococcus*, and *Mycobacterium* have capabilities to degrade diverse organic compounds. White-rot fungi such as *Trametes*, *Phanerochaete*, produce extracellular oxidative enzymes like laccases, peroxidases, which are extremely effective against recalcitrant aromatics. Bioremediation encompasses a suite of biologically-driven processes as described in the following-

3.3.1. Microbial bioremediation techniques:

- **Biodegradation:** This is the enzymatic transformation of organic pollutants to less harmful molecules through microbial digestion. Key enzymes include oxygenases, hydrolases, dehydrogenases, and peroxidases.
- **Co-metabolism:** microorganisms degrade a pollutant chemical simultaneously while metabolizing a primary substrate.
- **Biosorption & bioaccumulation:** it is a process of passive adsorption of metals or organics to biomass. It is useful for removing heavy metals and some hydrophobic compounds.
- **Enzymatic bioremediation:** This procedure is application of purified or immobilized enzymes such as, laccases, peroxidases, etc. to catalyze pollutant breakdown. [19, 20, 21, 22]

3.3.2. Bioremediation Strategies:

- **Natural attenuation** strategy relies on in-situ microbial communities in the water bodies; requires constant monitoring and often is a slow process.
- **Biostimulation** is the process of addition of nutrients, electron donors or acceptors, or environmental adjustments such as change in pH, oxygenation level, to stimulate indigenous degraders in the water body.
- **Bioaugmentation** is the process of seeding an existing water body with specialized microbial strains that possess desired degradation pathways. Successful cases often require consideration of survival, competition, and environmental compatibility.
- **Constructed wetlands** are engineered ecosystems combining plants, substrates, and microbial biofilms to remove emerging pollutants via sorption, plant uptake, and microbial degradation processes. Constructed wetlands are low-cost and suitable for decentralized treatment and polishing of secondary effluents.
- **Phyto-remediation** strategy uses plants such as riparian vegetation, aquatic macro-phytes, to uptake, transform, or immobilize contaminants; and the effectiveness of this process varies by compound and plant species.
- **Bioreactors and bio-film reactors:** This process applies plug-flow or batch bioreactors with aerobic or anaerobic or anoxic mechanism, membrane bioreactors and sequencing batch reactors that are optimized for micropollutant removal through controlled conditions. [23, 24, 25, 26]

4. Conclusion

Emerging pollutants present complex technical and regulatory challenges due to their diversity, low-dose bioactivity, and in many cases persistence. Bioremediation — in its many manifestations (microbial, enzymatic, phytoremediation, constructed wetlands, and engineered bioreactors) — offers sustainable, often low-cost pathways to mitigate many EPs. However, highly persistent organic substances remain a key limitation for purely biological approaches and require hybrid or novel solutions. Future progress hinges on combined advances in analytical detection, mechanistic understanding, enzyme and microbial engineering, and integrated treatment approaches aligned with stronger monitoring and policy frameworks. As bioremediation is the most sustainable technique and most suitable to achieve sustainable environment, it is highly important to rely on and advanced research techniques need to be implemented.

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