

Fate of Organic Micropollutants in Aquatic Environment: Policies and Regulatory Measures



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Abstract Aquatic environments are pervasively contaminated with organic micropollutants (OMPs), a wide array of substances encompassing pharmaceuticals, personal care products, and pesticides. These contaminants have the potential to cause harm to aquatic organisms and pose risks to human health. This chapter comprehensively overviews OMPs' sources and fates (roots and products) in aquatic environments. The chapter begins by discussing the sources of OMPs, which include

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point sources such as wastewater treatment plants and industrial discharges as well as non-point sources such as agricultural runoff and atmospheric deposition. Moreover, the fate of OMPs in aquatic environments, including sorption, biodegradation, and photodegradation, was described. Furthermore, this review encompassed the examination of analytical methodologies employed for the identification and quantification of OMPs in aquatic ecosystems, including other methods such as advanced technological and biological methods and newer methods such as passive samplers and high-resolution mass spectrometry. We conclude by highlighting the challenges and future directions in the study of OMPs in aquatic environments, including the need for more comprehensive field and laboratory research, the development of more effective treatment technologies, and the integration of chemical and biological approaches to assess the potential risks of OMPs. Finally, this chapter will provide a valuable resource for researchers, policymakers, and stakeholders interested in understanding the sources and fates of OMPs in aquatic environments.

Keywords Aquatic environment · Fate · Sources · Organic micropollutants

1 Introduction

The aquatic environment is a complex system that supports a wide range of organisms and is essential in sustaining life on Earth (Agüera et al. 2020). However, this ecosystem is constantly threatened by various human activities, including releasing organic micropollutants (OMPs) into water bodies (Rasheed et al. 2019). OMPs encompass a wide array of substances, which span across different categories, such as pharmaceuticals, personal care products, pesticides, and industrial chemicals (Tripathi et al. 2020). They are present in aquatic environments at low concentrations, typically ranging from ng/L to µg/L. These compounds can originate from various sources, including agricultural and industrial activities, urban runoff, and wastewater discharges (Gautam and Anbumani 2020). They are of concern due to their potential adverse effects on aquatic organisms and their potential to enter the food chain and ultimately impact human health (Ajibade et al. 2021a). OMPs are ubiquitous in surface waters, groundwater, and even drinking water sources, posing a potential risk to human health and the environment.

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The fate and behavior of OMPs in aquatic environments are influenced by various factors, including their physicochemical properties, environmental conditions, and other substances in the water (Kümmerer et al. 2019). OMPs can undergo photodegradation, biodegradation, and chemical transformations, forming potentially harmful degradation products. Moreover, they can be transported over long distances, facilitating their spread across different water bodies and ecosystems (Omotade et al. 2023). The potential risks associated with OMPs in aquatic environments have prompted significant research efforts to understand their occurrence, fate, and effects on the environment and human health. Analytical methods have been developed to detect and quantify OMPs in water samples, and various treatment technologies have been proposed to remove them from wastewater and drinking water sources (Ngo et al. 2020). However, managing OMPs in aquatic environments remains a significant challenge due to their diverse nature, low concentrations, and environmental persistence.

This chapter aims to provide a comprehensive overview of the sources and fates of OMPs in the aquatic environment. It covered different types of OMPs, their sources, and the pathways they enter into the water bodies. The review also probed the fate of these compounds in the aquatic environment, including the processes that influence their degradation, transformation, and accumulation. Additionally, the review explored the potential risks posed by OMPs to aquatic life and human well-being and the current regulatory frameworks to manage these compounds. Finally, this chapter will provide a valuable resource for researchers, policymakers, and stakeholders interested in understanding the complex issue of OMPs in the aquatic environment.

2 Sources of OMPs in Aquatic Environments

Organic micropollutants (OMPs) are a class of chemical compounds typically found in low concentrations in aquatic environments but can significantly impact the health of aquatic organisms and human populations. These compounds include a wide range of chemicals, such as pharmaceuticals, pesticides, industrial chemicals, personal care products, and other emerging contaminants (Singh et al. 2021a).

According to reports, OMPs are virtually never eliminated by traditional treatment techniques (Kim et al. 2008; Wenzel et al. 2008; Ahmed et al. 2020; Pathak et al. 2020a, b). With OMP concentrations ranging from ng/L to g/L, these treated or untreated effluents may be released into rivers and coastal areas (Galindo-Miranda et al. 2019; Roy et al. 2020), and surface outflow and deep-well injection of the effluent have the potential to contaminate treated potable water resources. This shows that these OMPs are present in drinking water. Historically, steroidal hormones and plasticizers have been found in surface water, groundwater, and potable water (Blessing and Baran 2022). Industries, municipal sewage, and agricultural practices can be recognized as the main origins of OMPs in water bodies (Fig. 1), though there are several sources of OMPs in aquatic ecosystems according to studies

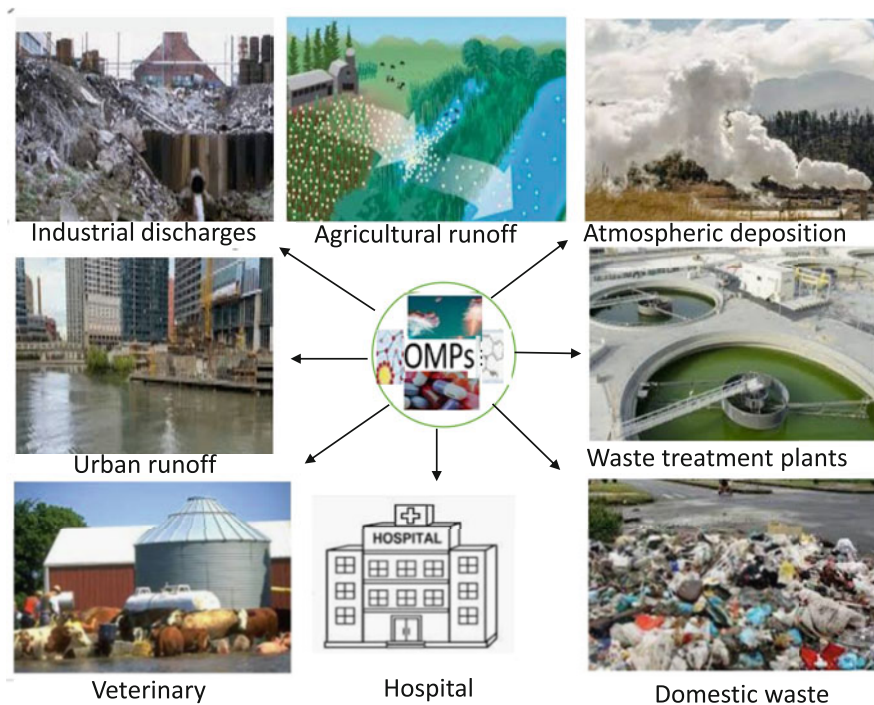


Fig. 1 Sources of organic micropollutants (OMPs) in aquatic environments

published earlier (Loraine and Pettigrove 2006; Agüera et al. 2020; Tripathi et al. 2020; Tröger et al. 2020), including:

1. **Industrial discharges:** Various pharmaceutical, chemical, and petrochemical industries generate OMPs as by-products of their manufacturing processes, which are discharged into nearby water bodies. These discharges can contain a wide range of chemicals, including heavy metals, pesticides, and organic solvents.
2. **Agricultural runoff:** Pesticides and fertilizers used in agriculture can be a significant source of OMPs in water bodies. These chemicals can enter waterways through erosion, runoff, or leaching from agricultural land.
3. **Atmospheric deposition:** OMPs can enter aquatic environments through atmospheric deposition, carried by wind and deposited through rainfall or dry deposition. This can include chemicals such as polycyclic aromatic hydrocarbons (PAHs), commonly found in urban areas due to vehicle emissions and other combustion sources.
4. **Wastewater treatment plants:** Wastewater treatment plants are a significant source of OMPs in water bodies (Singh et al. 2021a,b). These facilities are designed to remove contaminants from wastewater, but many OMPs can pass through treatment processes and end up in receiving waters.

5. Urban runoff: Urban areas can be a significant source of OMPs due to the widespread use of personal care products, pharmaceuticals, and other chemicals. These compounds can enter waterways through stormwater runoff, which can carry pollutants from roads, parking lots, and other impervious surfaces (Gautam and Anbumani 2020; Singh et al. 2021a, b, c).

Moreover, these origins can be classified into non-point sources, which involve widespread discharges from diffusive sources, or discreet sources, such as industrial discharges and effluents from domestic wastewater treatment facilities. As Rasheed et al. (2019) noted, agricultural pesticides, for example, can be extensively dispersed in relatively low yet potentially hazardous concentrations, leading to persistent impacts.

As shown in Fig. 1, numerous solid, liquid, and gaseous organic pollutants will also be produced due to industrial, agricultural, atmospheric, urban, wastewater treatment plant, veterinary, hospitals, and other domestic activities. Organic pollutants have various pathways to enter the soil and water environment, either directly or indirectly. These channels include the deposition of atmospheric particles through dry and wet processes, the use of pesticides and fertilizers, the application of sewage sludge in agricultural practices, oil extraction and transportation, as well as leaks from landfill sites (Tripathi et al. 2020; Singh et al. 2021a).

Introducing organic contaminants into the soil environment poses potential risks to human health due to their impact on soil structure and ecological functioning. This can lead to decreased productivity, reduced ecological capacity, and the subsequent transfer of these pollutants through the food chain to humans via crops. Processes such as adsorption/desorption, degradation/accumulation, dissolution/precipitation, and complexation/chelation play a role in the transport, distribution, and modification of OMPs along ecohydrological interfaces (Kumar et al. 2020; Sasi et al. 2020). The characteristics of the various media at the interfaces significantly impact how organic contaminants migrate and change.

3 Environmental Classification of Organic Pollutants

Since a few years ago, developing nations have generated, used, imported, and released various carbon-based pollutants into the environment. Due to their potential for bioaccumulation, persistence, and noxiousness, carbon-based contaminants have been significant environmental hazards, posing several technical and societal concerns. There is a lack of comprehensive understanding of the ecological and toxicological impacts of OMPs on the environment and human health (Liu et al. 2019). Therefore, it is crucial to assess the impact of carbon-based pollutants on human health and ecosystem health, such as insecticides, endocrine-disrupting contaminants (EDCs), and other pollutants (Kaleniecka and Zarzycki 2015). Carbon-based contaminants are very resistant to putrefaction in both their immediate and riverine environments, ecology, soils, the food chain, and inside people's bodies for a long

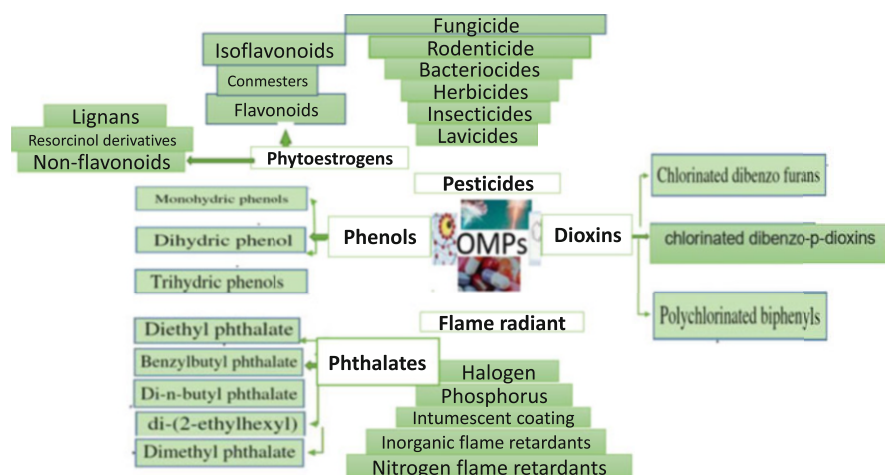


Fig. 2 Types of organic micropollutants (OMPs) in the aquatic ecosystems

time. The principal categories of organic chemicals contaminating water bodies are discussed in the following sections and shown in Fig. 2.

4 Fate and Behavior of OMPs and Technologies for Removing OMPs from Aquatic Environments

Organic micropollutants (OMPs) can undergo various natural processes, transforming into less dangerous and destructive forms. The contaminants are usually broken down into smaller molecules by these mechanisms. They may be used to treat these substances in various ways and are categorized as photochemical reactors, enhanced oxidation technology, photocatalytic degradation, etc. (Liu et al. 2019; Panidepu et al. 2020; Ram et al. 2020). An improved understanding of the fate and behavior of OMPs in aquatic environments, including their sources, transport pathways, and transformation products, is essential. Development of new analytical methods and tools for detecting and quantifying OMPs at low concentrations in water samples. Advancements in treatment technologies for removing OMPs from water, including membrane filtration, advanced oxidation processes, and bioremediation (Varjani and Sudha 2020).

Organic micropollutants (OMPs) can persist in the environment for long periods and accumulate in the food chain, posing potential risks to human health and the environment. OMPs can be difficult to detect and quantify at low concentrations, making it challenging to assess their environmental impact (Nguyen et al. 2020). Treatment technologies for removing OMPs can be expensive and energy-intensive and may not be effective at removing all types of OMPs. There is a need for more research regarding the effects over an extended duration of OMPs on aquatic

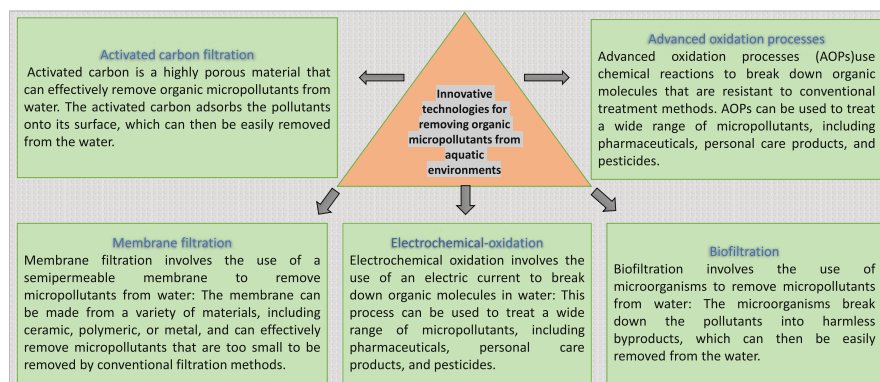


Fig. 3 Innovative technologies that are being developed and used for removing OMPs from aquatic environments

ecosystems and the wider environment, as well as on the potential risks associated with emerging contaminants, such as microplastics and pharmaceuticals. The fate and behavior of OMPs in water bodies are influenced by a variety of physical, chemical, and biological processes, including adsorption, desorption, biodegradation, photodegradation, and others, as described in Fig. 3.

4.1 Adsorption

Adsorption is the process by which OMPs attach to the surface of solids, such as sediments or suspended particles. This process can reduce the concentration of these compounds in the water column and affect their bioavailability to aquatic organisms (Kaleniecka and Zarzycki 2015). Adsorption is influenced by factors such as the organic micropollutant's properties, the adsorbing surface's properties, and environmental conditions such as pH and temperature.

The adsorption process entails intricate surface interactions and hydrophobic forces acting on the surfactant or polymer (Kumar et al. 2020). Batch tests were conducted for effluents containing 9 ng/L of butylparaben and 173 ng/L of caffeine (Kumar et al. 2020). Around 94% of the OMPs were removed. Regardless of the baseline concentrations of the compounds, higher dosages of powdered activated carbon (PAC) improved the removal percentages of micropollutants. Caffeine, acetaminophen, sulfamethoxazole, and sulfamethazine were found to fit in a linear isotherm, while naproxen, diclofenac, 2,4-D, triclocarban, and atrazine were found to fit in a hydrophobic isotherm (Varjani and Sudha 2020).

The interactions between the particle and the contaminant play a major role in eliminating trace contaminants. The removal effectiveness of activated carbon can be reduced by competition for adsorption sites and/or pore blockage (through particle solids) (Kumar et al. 2020; Varjani and Sudha 2020). Granular activated

carbon (GAC) that has undergone steam treatment has a better absorption capacity, according to Panidepu et al. (2020). Regular GAC regeneration seems to be essential for preserving low micropollutant breakthroughs. Additionally, removal performance was influenced by the carbon type, compound surface load, and year of operation (Ngo et al. 2020). Changes can influence this process in environmental conditions such as pH, temperature, and the presence of other chemicals. Desorption can increase the concentration of OMPs in the water column and make them more available for uptake by aquatic organisms.

4.2 Membrane Operations

In membrane-based processes for micropollutant removal, membrane adsorption, pore size, and repulsion charging are commonly employed mechanisms. The effectiveness of removing micropollutants through membrane processes depends on various factors, including the type of membrane process used, membrane properties, potential pore clogging, operating conditions, and specific characteristics of the micropollutants. These factors collectively influence the efficiency of micropollutant removal in membrane-based systems (Khoo et al. 2022).

The turbidity removal from water can be effectively accomplished using microfiltration (MF) and ultrafiltration (UF) techniques. However, these methods fail to eliminate micropollutants due to their molecular sizes. To address the removal of organic micropollutants, alternative mechanisms come into play, such as the interaction of micropollutants with natural organic matter (NOM) or their adherence to membrane polymers. In the absence of NOM, Kumar et al. (2020) investigated the efficacy of UF in removing ibuprofen and estradiol. The hydrophilic UF membrane showed zero clearance for ibuprofen and an 8% clearance for estradiol. However, the hydrophobic membrane demonstrated an increase in removal efficiency, with ibuprofen and estradiol reaching approximately 25% and 80% clearance, respectively.

Furthermore, Kümmerer et al. (2019) conducted a study on the removal of micropollutants from domestic wastewater using MF and reverse osmosis (RO) processes for potential reuse. For example, di(2-ethylhexyl)phthalate experienced a reduction of up to 50% after MF treatment. The combination of MF and RO systems enhanced the efficiency of micropollutant removal. Ibuprofen and nonylphenol exhibited the lowest removal efficiency at 5%, while most other micropollutants, except for mefenamic acid and caffeine, showed substantial removal effectiveness of over 95%, according to another investigation on the combination of MF and RO systems conducted by Wanda et al. (2017).

4.3 Biodegradation

Biodegradation is the process by which microorganisms break down OMPs in aquatic environments. This process can be influenced by factors such as the chemical structure of the organic micropollutant, the types and abundance of microorganisms present, and environmental conditions such as temperature and nutrient availability. Biodegradation can reduce the concentration of OMPs in the water column and can also result in the formation of biodegradation by-products.

4.3.1 Photodegradation

Photodegradation is the process by which OMPs are broken down by exposure to sunlight. This process can be influenced by factors such as the organic micropollutant's chemical structure, the sunlight's intensity and wavelength, and environmental conditions such as temperature and the presence of other chemicals. Photodegradation can reduce the concentration of OMPs in the water column and form photodegradation by-products. This method removes carbon-based pollutants via photocatalytic degradation, despite several traditional physical, chemical, and biological procedures being established to treat contaminated water (Gonzalez-Gil et al. 2020; Ngo et al. 2020). Carbon-based pollutants can be eliminated, including endocrine-disrupting chemicals (EDCs), pesticides, and herbicides. Researchers have recently started to pay more attention to it (Pitarch et al. 2016).

Although much research on titanium dioxide (TiO_2) photocatalysis has been done in lab settings, its use in production requires limitations. Given its capacity for accelerating processes without being edible, a photocatalyst is described as a material activated by adsorbing photons. Tröger et al. (2020) employed this method to degrade the chemical compound bisphenol-A (BPA). BPA can potentially enter water bodies through sewage discharges from factories engaged in the production of polyvinyl chloride, phenol, phenoplasts, concentrated polyester mastics, and thermal paper, among other products. In freshwater, bisphenol-A photolysis could be a crucial yet undetected mechanism (Singh et al. 2021b). Alkylphenols have been widely used in complexes in recent years to study the photoreactivity of dissolved organic matter (DOM) scarcity, and the inability of well-organized and lucrative catalysts for the greater efficiency of photons to work in the broader solar spectrum prevented several uses of the treatments (Tiwari et al. 2020; Singh et al. 2021b). More study is required on how water components degrade to understand the application process better.

4.4 *Advanced Oxidation Technology*

Semiconducting oxides have been increasingly focused on in recent years as photocatalysts for potential solar energy conversion as well as ecosystem decontamination. According to Singh et al. (2021b), semiconductor-variegated photocatalysis offers enormous promise for treating carbon-based water contaminants. This procedure, sometimes called an advanced oxidation process (AOP), is suitable for oxidizing a wide variety of carbon-based compounds. It has been demonstrated to be interesting due to its effectiveness in difficult carbon-based compounds. Numerous studies have been conducted on the use of diverse photocatalytic oxidation processes for the decomposition and mineralization of recalcitrant carbon-based compounds (Singh et al. 2021b).

Ultraviolet (UV) or solar light can both be utilized to power the photocatalytic reactor. The photo-oxidation of water contaminants with carbon bases is of relevance to the solar photocatalytic reactor. According to Yadav et al. (2020), these receptacle types can be divided into concentrating and non-concentrating receptacles. Although sophisticated oxidation technology has been employed in developed countries, it is not typically used in underdeveloped nations because of energy consumption and running expenses (Kaleniecka and Zarzycki 2015).

4.5 *Photochemical Reactors*

The molecules of the chemical species already present in the solutions or with the use of catalysts interact with photons of the appropriate energy levels to introduce free radical mechanisms into the photo-activated chemical process (Sasi et al. 2020). The slurry of discrete solid semi-conductor components in the liquid phases may be used to authorize this reaction, but the performance of the reactors may be difficult due to the slurry's poor radiation efficiency. Additional mechanisms aid the breakdown of organic contaminants.

4.6 *Organic Pollutant Degradation by Microbial Enzymes*

Organic pollutant degradation by microbial enzymes is a natural process that involves the use of enzymes produced by microorganisms to break down and degrade various types of organic pollutants (Singh et al. 2021b). Microbial enzymes are highly specific and can target and degrade extensive variety of organic compounds, encompassing hydrocarbons, pesticides, and industrial chemicals. The process of organic pollutant degradation by microbial enzymes typically involves three stages: (1) the production of enzymes by microorganisms in response to the presence of organic pollutants; (2) the enzymatic breakdown of the pollutants into

simpler, less toxic compounds; and (3) the assimilation of the degraded compounds by microorganisms as a source of energy and nutrients. This process is highly effective in removing organic pollutants from the environment and has been widely used in bioremediation applications. Bioremediation is the use of microorganisms to remove or neutralize environmental pollutants. It is a cost-effective and environmentally friendly alternative to traditional remediation methods, such as chemical treatment or incineration (Agüera et al. 2020; Fortunato et al. 2021).

Organic micropollutants (OMPs) have a great sensitivity to a wide variety of substrates (contaminants); microbial enzymes play a beneficial role in the bioremediation of environmental pollutants originating from various sources. By creating favorable circumstances that reduce the reaction's activation energy, enzymes serve as biological catalysts that make it easier to convert substrates into products (Singh et al. 2021b). An enzyme comprises at least one polypeptide component and can be either a protein or a glycoprotein. These are some few significant enzymes that are involved in bioremediation: multi-copper proteins called laccases can oxidize a variety of aromatic and nonaromatic substances, such as phenols, halogenated phenols, aromatic amines, nitro-substituted compounds, organophosphorus compounds, polycyclic aromatic hydrocarbons (PAHs), chlorinated hydroxybiphenyls, bisphenol-A and nonylphenol, hydroxyphenylureas, endocrine disruptors, pesticides, and insecticides (Pathak et al. 2020a, b).

Cellulases are enzymes that microorganisms such as *Bacillus* strains, *Trichoderma*, and *Humicola* fungi produce. These enzymes offer a pivotal role in the breakdown of cellulosic materials, which are abundant in waste products. By catalyzing the hydrolysis of cellulose, cellulases can convert these waste materials into a usable form, such as food. Apart from their role in waste management, cellulases find applications in industries like paper and pulp. In the paper recycling process, cellulases are employed to remove ink from the fibers, facilitating the production of high-quality recycled paper. In monooxygenases, there are two subclasses: flavin-dependent monooxygenases and P_{450} monooxygenases. Monooxygenases are enzymes that introduce a single oxygen atom into a substrate molecule. The flavin-dependent monooxygenases and P_{450} monooxygenases are known for their ability to perform such oxygenation reactions. One specific monooxygenase enzyme called methane monooxygenase (MMO) stands out for its capability to degrade hydrocarbons. MMO is particularly effective in breaking down various types of hydrocarbons, including substituted methane, alkanes, cycloalkanes, alkenes, haloalkenes, ethers, as well as aromatic and heterocyclic hydrocarbons. This enzyme plays a significant role in the natural biodegradation of hydrocarbon pollutants and holds a considerable significance in bioremediation procedures (Singh et al. 2021b).

In conclusion, organic pollutant degradation by microbial enzymes is a natural process that offers a promising solution for the remediation of polluted environments. It is a sustainable approach that can help reduce the impact of human activities on the environment.

4.7 Other Treatment Methods for Natural Pollution

Due to the diversity of sources of organic pollutants and the presence of chemical complexity, the membership of microbial communities and their ability to synthesize or degrade organic compounds may be more diverse (Singh et al. 2021b). A summary of critical technologies for treating OMPs in water is provided in Table 1.

Depending mainly on the ability of microorganisms to degrade/detoxify or transform pollutants, they can also be exposed to pollutants and their presence (Singh et al. 2021b). It can be used as an in situ (repair in situ) and ex situ (repair elsewhere) restoration technique. Bioremediation includes (Singh et al. 2021a, b, c) decay (a natural degradation process that can be observed by reducing the amount of pollution over time), biostimulation (intentional initiation of pollution by adding water, nutrients, and electricity or electron donor's biodegradation), and bioaugmentation (addition of laboratory-grown microorganisms with degradative potential). There are publications on the various removal methods for OMPs. The information was acquired from Journals between 2011 and 2022, adopted and modified as shown in Fig. 4.

4.7.1 Bioattenuation

Biological attenuation includes various bio-physicochemical processes that reduce the concentration, toxicity, volume, or concentration of pollutants (Blessing and Baran 2022). The techniques encompass adsorption, chemical or biological stabilization, volatilization, aerobic and anaerobic biodegradation, as well as the contaminant transformation. The factor of time does not impose any limitations on these processes and is often used in low-contamination sites where no other method is available (Kümmerer et al. 2019). During decay (natural decay), pollutants are converted into harmless or immobile forms. This change and fixation process is primarily due to microbial biodegradation (Smets and Pritchard 2003) and, to some extent, due to reactions with naturally occurring chemicals dispersed throughout the soil medium. The natural decay method works for specific pollutants. While it is acknowledged as an effective remedy for petroleum products like benzene, toluene, ethylbenzene, and xylenes (BTEX) (Kaleniecka and Zarzycki 2015), this approach may not be applicable to numerous other compound classes. The duration for natural degradation varies depending on the specific site conditions. Severely contaminated sites may not require drastic remediation measures, and attenuation is economically friendly (Singh et al. 2021b; Blessing and Baran 2022).

4.7.2 Biostimulants

Biostimulation refers to the method through which advantageous microorganisms alter the environment to improve bioremediation. This is accomplished by various

Table 1 Summary of key technologies for treating organic micropollutants (OMPs) in water system

Technology	OMPs	Description	Advantages	Disadvantages	References
Activated carbon adsorption	- Pesticides (e.g., atrazine, simazine) - Pharmaceuticals (e.g., ibuprofen, carbamazepine)	OMPs are adsorbed onto activated carbon particles, then removed from the water	Effective at removing a wide range of organic contaminants	Can become saturated and require replacement or regeneration; not effective at removing all types of pollutants (e.g., some pesticides)	(Kalenicka and Zarzycki 2015)
Membrane filtration	- Endocrine-disrupting compounds (e.g., bisphenol-A) - Pharmaceuticals (e.g., antibiotics, hormones)	Water is passed through a membrane that selectively removes organic micropollutants	Can be effective at removing a wide range of contaminants; can be combined with other treatment processes for improved removal efficiency	Requires regular maintenance and cleaning to prevent fouling; may not be effective at removing certain contaminants (e.g., dissolved organic compounds)	(Roy et al. 2020)
Ultraviolet (UV) irradiation	- Polycyclic aromatic hydrocarbons (PAHs) - Chlorinated solvents (e.g., trichloroethylene)	UV light is used to break down OMPs into simpler compounds	Effective at removing certain classes of contaminants, such as pharmaceuticals and personal care products	May not be effective at removing all types of contaminants; it requires careful control of UV dosage to prevent the formation of harmful by-products	(Liu et al. 2019)
Advanced oxidation processes (AOPs)	- Pesticides (e.g., chlorpyrifos, diazinon) - Pharmaceuticals (e.g., diclofenac, sulfamethoxazole)	Chemical reactions are used to break down OMPs into simpler compounds	Can be effective at removing a wide range of contaminants; can be combined with other treatment processes for improved removal efficiency	Can be expensive and energy-intensive; it requires careful control of reaction conditions to prevent the formation of harmful by-products	(More and Tyagi 2020)
Ozonation	Cyanotoxins (e.g., microcystins)	Ozone gas is used to oxidize and break down organic micropollutants	Can be effective at removing a wide range of contaminants; can be	It can be expensive and energy-intensive; it requires careful control of	(Liu et al. 2019)

(continued)

Table 1 (continued)

Technology	OMP's	Description	Advantages	Disadvantages	References
	Personal care products (e.g., triclosan)		combined with other treatment processes for improved removal efficiency	ozone dosage to prevent the formation of harmful by-products	
Biological treatment	- Nitrosamines (e.g., NDMA) - Aromatic amines (e.g., aniline)	Microorganisms are used to break down organic micropollutants	Can be effective at removing a wide range of contaminants; can be relatively low-cost and energy-efficient	Requires careful control of treatment conditions to ensure optimal microbial activity; may not be effective at removing certain types of contaminants	(More & Tyagi 2020)
Chemical coagulation/flocculation	- Heavy metals (e.g., lead, copper) - Colloids and suspended solids	Chemicals are added to water to form aggregates that can be removed by sedimentation or filtration.	It can be effective at removing certain types of contaminants, such as dissolved organic matter and some metals	It may not be effective at removing all contaminants (e.g., some pesticides); it can generate large volumes of sludge that require disposal	(Jorge et al. 2023)
Electrochemical treatment	- Chlorinated solvents (e.g., perchloroethylene) - Petroleum hydrocarbons (e.g., benzene)	Electrical current is used to oxidize or reduce organic micropollutants	Can be effective at removing a wide range of contaminants; can be relatively low-cost and energy-efficient	Requires careful control of treatment conditions to prevent the formation of harmful by-products; may not be effective at removing certain types of contaminants (e.g., some pesticides)	(Ngo et al. 2020)
Ion exchange	- Perfluoroalkyl and poly-fluoroalkyl substances (PFAS) - Heavy metals	OMPs are removed from water by exchanging ions with a resin material	It can effectively remove certain contaminants, such as heavy metals and some pesticides	It can become saturated and require replacement or regeneration; it may generate large volumes of	(Ahmed et al. 2020)

Advanced oxidation with hydrogen peroxide (H_2O_2)	(e.g., cadmium, nickel) – Pharmaceuticals (e.g., ibuprofen, naproxen) – Endocrine-disrupting compounds (e.g., estrone)	Hydrogen peroxide is used in combination with UV or ozone to break down organic micropollutants	Can be effective at removing a wide range of contaminants; can be combined with other treatment processes for improved removal efficiency	wastewater containing contaminants Requires careful control of H_2O_2 dosage to prevent the formation of harmful by-products; can be expensive and energy-intensive	(Yadav et al. 2020)
Reverse osmosis (RO)	– Salts and minerals (e.g., sodium, calcium) – Microorganisms (e.g., bacteria, viruses)	Water is forced through a membrane that selectively removes organic micropollutants	Can be effective at removing a wide range of contaminants; can be combined with other treatment processes for improved removal efficiency	It can be expensive and energy-intensive; it requires regular maintenance and cleaning to prevent fouling	(Song et al. 2020)
Wetland's treatment	– Nutrients (e.g., nitrogen, phosphorus) – Organic matter (e.g., humic acids)	Water is treated by passing through a wetland area containing plants and microorganisms that can remove contaminants	Can be effective at removing a wide range of contaminants; can be relatively low-cost and energy-efficient	Requires large land area; may not be effective at removing all types of contaminants; requires careful management to prevent release of contaminants into the environment	(Breitholtz et al. 2012; Liu et al. 2019; Ajibade et al. 2021b,c; Nwogwu et al., 2022; Ajibade et al. 2023a,b; Bao et al. 2023)

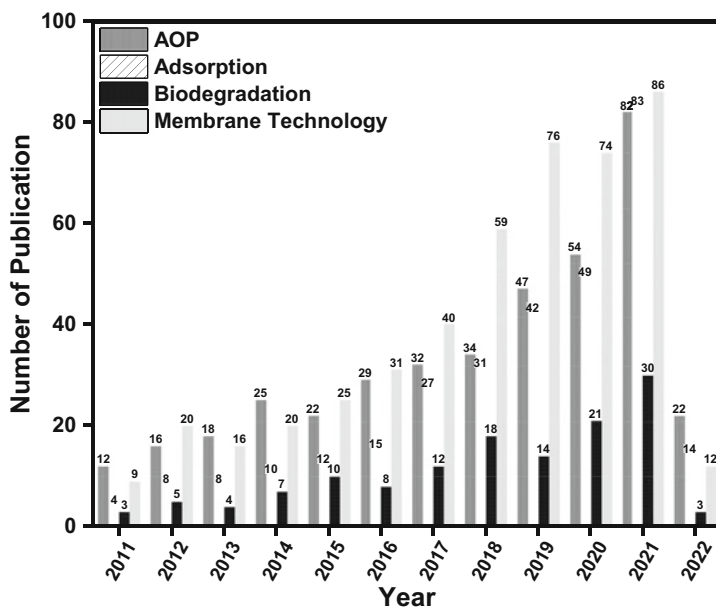


Fig. 4 Publications on the various removal methods for OMPs. The information was assessed based on acquired Journals between 2011 and 2023 (Adopted and modified from Khoo et al. (2022))

means, such as introducing specific nutrients and electron acceptors of different types, such as altering the pH, phosphorus, nitrogen, oxygen, or carbon, and making changes to the organism's body structure. On the other hand, biostimulants are naturally occurring substances that can enhance plants' growth and health (Gautam and Anbumani 2020). They are derived from various sources such as seaweed, plant extracts, and microorganisms. Biostimulants have become increasingly popular in agriculture for their ability to improve crop yields and quality (Singh et al. 2021c). However, they can also be used to treat OMPs in aquatic environments.

Organic micropollutants (OMP) are compounds that are present in low concentrations in the environment but can have harmful effects on aquatic organisms. These compounds can come from a variety of sources such as pharmaceuticals, personal care products, and pesticides. Traditional methods of treating micropollutants in aquatic environments, such as physical and chemical processes, can be expensive and energy-intensive. Biostimulants can be used to treat OMPs through a process called biodegradation. Biodegradation is the breakdown of organic compounds by microorganisms into harmless substances such as water and carbon dioxide. Biostimulants can enhance the growth and activity of microorganisms, thereby increasing the rate of biodegradation of OMPs (Singh et al. 2021b,c).

Several studies have shown that biostimulants can effectively treat OMPs in aquatic environments. For example, biostimulation, commonly known as bioremediation, can be further improved through bioaugmentation. This EPA-approved

approach is primarily utilized for reversing oil or gas spills. While biostimulation is often linked to hydrocarbon remediation and promoting microbial growth, it also holds promise for addressing regular pollutant discharges, particularly pesticides and herbicides (Pathak et al. 2020a, b). To stimulate bacterial destruction, nutrients in the form of chemical fertilizers (water-soluble KNO_3 , NaNO_3 , NH_3NO_3 , K_2HPO_4 , and MgNH_4PO_4) and quick-release customizable and lipophilic substances (Inipol EAP22) were added (Ram et al. 2020).

In conclusion, biostimulants can be a cost-effective and environmentally friendly solution for treating OMPs in aquatic environments. Further research is needed to explore the full potential of biostimulants in this application and to develop effective strategies for their application.

4.7.3 Bioaugmentation

In contaminated sites with no history of exposure, biological responses are often delayed for weeks or months. The concept of “soil activation” involves cultivating biomass from a small portion of contaminated soil and employing it as a biologically enriched starter culture for the corresponding soil. This method leverages the adaptation of soil microbiota exposed to environmental pollutants, such as hydrocarbons, to serve as a microbial resource for remediating hydrocarbon-contaminated soils.

4.7.4 Trace Pollutants

Encouraging in situ microbial growth offers the hope of converting various dissolved and absorbed pollutants into harmless products. The approach entails the introduction of chemical substances (electron acceptors and/or electron donors and nutrients) into polluted soil to stimulate microbial proliferation. Carbon sources and nutrients are essential for organisms’ growth and electron donors and acceptors (Singh et al. 2021b; Blessing and Baran 2022). In addition to compounds with natural forms, many pollutants can also fulfill these growth needs.

5 The Role of Environmental Factors in the Fate of OMPs

Environmental factors play a crucial role in the fate and behavior of OMPs in aquatic environments; these factors can affect organic micropollutants’ physical and chemical properties, their interactions with other compounds in the water column, and their uptake by aquatic organisms. Some of the critical environmental factors that can influence the fate of OMPs according to several studies (e.g., Rasheed et al. 2019; Tröger et al. 2020; Fortunato et al. 2021) include:

- i. pH: The pH of the water can affect the solubility and reactivity of organic micropollutants. For example, acidic conditions can increase the solubility of some organic micropollutants, while basic conditions can cause them to degrade more quickly.
- ii. Temperature: Temperature can affect the rate of both biotic and abiotic processes that influence the fate of OMPs in aquatic environments. Higher temperatures can increase the rate of biodegradation and photodegradation while also decreasing the solubility of some organic micropollutants.
- iii. Salinity: Salinity can affect the solubility and adsorption of OMPs in aquatic environments. In general, OMPs are more soluble in freshwater than in seawater, but they can also adsorb more strongly to suspended particles in seawater.
- iv. Dissolved organic matter (DOM): Dissolved organic matter (DOM) can compete with OMPs for adsorption to solids or uptake by aquatic organisms. The presence of DOM can also influence the photodegradation rate and organic micropollutants' biodegradation.
- v. Oxygen concentration: The concentration of dissolved oxygen in the water can affect the rate of biodegradation of organic micropollutants. Low oxygen concentrations can limit the activity of aerobic microorganisms, which can slow the rate of biodegradation.
- vi. Redox potential: The water's redox potential can influence organic micropollutants' biodegradation. OMPs are generally more easily biodegraded under aerobic conditions (high redox potential) than under anaerobic conditions (low redox potential).
- vii. Light intensity: The intensity and wavelength of light can affect the photodegradation rate of organic micropollutants. High-intensity UV light can quickly break down many OMPs than low-intensity visible light.

6 Analytical Methods for Detecting OMPs in Aquatic Environments

Organic micropollutants (OMPs) are of concern due to their potential adverse effects on aquatic organisms and human health (More and Tyagi 2020). Therefore, it is essential to develop analytical methods for detecting OMPs in aquatic environments. Several analytical methods are available for detecting OMPs in aquatic environments. These methods can be broadly classified into non-targeted and targeted methods. Non-targeted methods are used to analyze the entire spectrum of organic compounds present in a sample without prior knowledge of the specific compounds of interest. These methods are useful for identifying unknown contaminants and monitoring changes in water samples' composition over time (Varjani and Sudha 2020). Non-targeted methods include techniques such as gas chromatography-mass spectrometry (GC-MS), liquid chromatography-mass spectrometry (LC-MS), and high-resolution mass spectrometry (HR-MS) (Agüera et al. 2020; Ahmed et al. 2020).

On the other hand, targeted methods are used to detect specific OMPs known to be present in a sample. These methods are useful when the identity of the contaminant is already known. Targeted methods include techniques such as gas chromatography-electron capture detection (GC-ECD), gas chromatography-flame ionization detection (GC-FID), and liquid chromatography with ultraviolet (LC-UV) or fluorescence detection (LC-FLD) (Ahmed et al. 2020; Kumar et al. 2020).

Regardless of the method used, detecting OMPs in aquatic environments typically involves several steps. These include sample collection, preparation, extraction, clean-up, and analysis. Sample collection involves taking representative water samples from the aquatic environment of interest. Sample preparation involves filtering the collected water samples to remove any particulate matter and adjusting the pH of the sample if necessary. Extraction involves the separation of the OMPs from the water matrix, usually using solid-phase extraction (SPE) or liquid-liquid extraction (LLE) (Rasheed et al. 2019; Ahmed et al. 2020). Clean-up involves the removal of any interfering compounds that may be present in the sample. Finally, analysis involves quantifying and identifying the target OMPs using the appropriate analytical technique.

Due to its affordability and capability for completely degrading pollutants, biological treatment techniques are still the favored or “tried and trusted” technology in wastewater treatment plants (WWTPs) today for removing organic matter and nutrients (Blessing and Baran 2022). Contaminants can be broken down into smaller and harmless molecules by microorganisms involved in biological processes, such as anaerobic, anoxic, and aerobic bacteria or mixtures. Most common biological treatments are not intended to remove trace quantities of OMPs but rather to remove ordinary pollutants from wastewater, such as chemical oxygen demand, nitrogen, and phosphate, as found in Fig. 5.

Figure 5 shows the maximum concentration of selected OMPs detected in wastewater treatment processes. The x-axis shows the different OMPs. According to the study, the y-axis shows the maximum concentration of the OMPs detected in each treatment process (Ngo et al. 2020). The selected OMPs include various types, such as pharmaceuticals, personal care products, pesticides, and industrial chemicals. Figure 5 would help to illustrate the effectiveness of different concentrations of OMPs in wastewater. For example, their study (Ngo et al. 2020) shows that specific micropollutants are effectively removed in primary treatment. Still, others require more advanced treatment processes, such as advanced oxidation or reverse osmosis, to achieve significant removal.

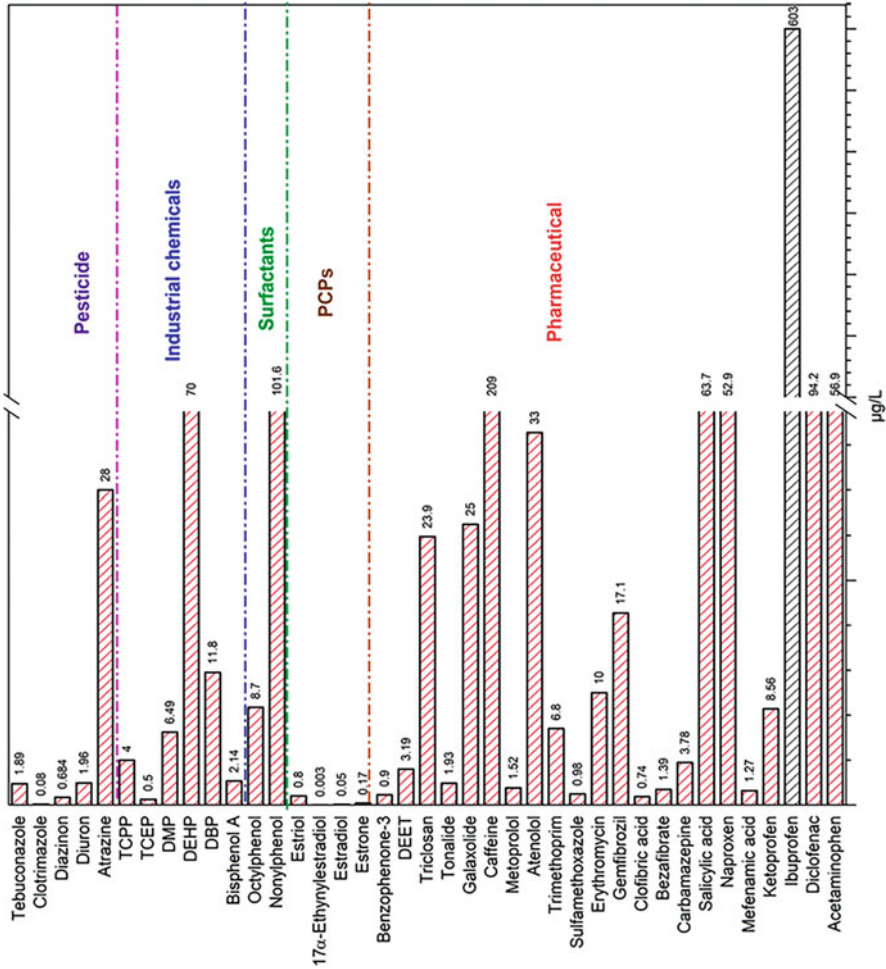


Fig. 5 The maximum concentration of selected OMPs detected in wastewater treatment processes. Modified from Ngo et al. (2020)

7 Risk Assessment and Regulation of OMPs in Aquatic Environments

The risk assessment and regulation of OMPs in aquatic environments is important for environmental protection and public health. OMPs are widely used in industry, agriculture, and households. They can enter aquatic environments through various pathways, such as direct discharge from industrial and municipal sources, runoff from agricultural land, and leaching from landfills. Once in aquatic environments, OMPs can pose a risk to aquatic organisms and human health (Ngo et al. 2020).

Risk assessment involves the evaluation of the potential risk posed by OMPs to human health and the environment. This includes assessing the likelihood of exposure to OMPs and the potential adverse effects that exposure may have. The risk assessment process involves several steps, including hazard identification, exposure assessment, and risk characterization. Risk identification involves identifying the potential adverse effects of OMPs on human health and the environment. Exposure assessment involves determining the extent and frequency of exposure to OMPs (Pathak et al. 2020a, b). Risk characterization involves combining the hazard and exposure assessments to estimate the overall risk posed by OMPs.

Regulation of OMPs in aquatic environments involves developing and implementing policies and regulations aimed at reducing the risk posed by these contaminants. Regulatory agencies set limits on the amount of OMPs that can be present in water, air, and soil. These limits are based on the results of risk assessments and take into account the potential adverse effects of OMPs on human health and the environment (Agüera et al. 2020). These regulations may also include measures to reduce the release of OMPs into the environment, such as requiring industries to use alternative chemicals or treatment methods to reduce OMP emissions.

In addition to regulations, there are also voluntary initiatives and programs aimed at reducing the presence of OMPs in aquatic environments. For example, the pharmaceutical industry has developed programs to reduce the discharge of pharmaceuticals into the environment (Wanda et al. 2017). These programs include developing alternative manufacturing processes, improving product design, and promoting proper disposal of unused medications.

8 Other Case Studies of OMPs in Some Specific Aquatic Environments

There have been many case studies on OMPs in various aquatic environments worldwide. Here are some examples: Publications from journals between 2011 and 2022 have discussed various removal methods for OMPs from water and wastewater (Fig. 4). These methods include advanced oxidation processes, biological treatment, membrane filtration, activated carbon adsorption, ozonation, electrochemical oxidation, biodegradation, and nanomaterials.

Advanced oxidation processes such as photolysis, catalytic oxidation, and ozonation effectively remove micropollutants from wastewater. Biological treatment using activated sludge and membrane bioreactors has also been effective in removing micropollutants. Membrane filtration and activated carbon adsorption are promising technologies for removing micropollutants from water. Ozonation and advanced oxidation processes can also be used for water treatment, but they can produce by-products that may pose health risks.

Electrochemical oxidation and nanomaterials are emerging technologies for the removal of micropollutants. These methods have shown promise in laboratory studies, but their practical application is still limited. Biodegradation of micropollutants by microorganisms is a natural process that can be enhanced using bioaugmentation or biostimulation techniques, but it may not be effective for all types of micropollutants. Overall, no single method can effectively remove all micropollutants from water. A combination of different treatment methods may be needed to remove micropollutants from water and wastewater completely. The chosen treatment method will depend on the specific micropollutants, their concentrations, and the water or wastewater's characteristics.

- (a) Rivers: The River Thames in the UK has been a focus of studies on OMPs. Researchers have found a range of OMPs in the river, including pharmaceuticals, personal care products, and pesticides (Ajibade et al. [2023a](#); Omotade et al. [2023](#)). In particular, the anti-inflammatory drug diclofenac has been found to be present in high river concentrations, which can negatively affect aquatic organisms.
- (b) Lakes: Lake Geneva in Switzerland and Sweden have been studied for the presence of OMPs. Researchers found high levels of the pesticide atrazine, which is used in agriculture, in the lake. Atrazine has been found to have endocrine-disrupting effects on aquatic organisms (Pathak et al. [2020a, b](#); Tröger et al. [2020](#); Khoo et al. [2022](#)).
- (c) Estuaries: The Mersey Estuary in the UK has been studied for the presence of OMPs. Researchers found a range of contaminants in the estuary, including polycyclic aromatic hydrocarbons (PAHs), commonly found in urban runoff and can negatively affect aquatic organisms (Wanda et al. [2017](#)).
- (d) Oceans: The North Pacific Gyre, also known as the Great Pacific Garbage Patch, has been studied for the presence of OMPs. Researchers found high levels of persistent organic pollutants (POPs) in the patch, including polychlorinated biphenyls (PCBs) and dichlorodiphenyltrichloroethane (DDT), which can have adverse effects on marine organisms and bioaccumulate in the food chain (Rasheed et al. [2019](#)).
- (e) Groundwater: The San Joaquin Valley in California has been studied for the presence of OMPs. Researchers found a range of contaminants in the groundwater, including pesticides and volatile organic compounds (VOCs), which can negatively affect human health (Loraine and Pettigrove [2006](#)).

9 Conclusion

In conclusion, studying the sources and fates of OMPs in aquatic environments is of utmost importance due to the widespread contamination and potential adverse effects on aquatic organisms and human health. Understanding the various sources, such as pharmaceuticals, personal care products, and pesticides, provides insights into the pathways through which these contaminants enter aquatic ecosystems.

Additionally, investigating these micropollutants' fate helps comprehend their behavior, persistence, and potential for bioaccumulation in the environment. The findings from research on OMPs in aquatic environments have highlighted the urgent need for effective monitoring and regulation to mitigate their impact. Strategies to reduce the release of these contaminants into water bodies, such as improving wastewater treatment processes and promoting the responsible use of pharmaceuticals and pesticides, are crucial for safeguarding the integrity of aquatic ecosystems and protecting human health. Furthermore, continued research and technological advancements are essential for enhancing our understanding of the complex interactions between OMPs and aquatic environments. This knowledge can guide the development of more efficient and sustainable approaches to minimize contamination and remediate affected areas. By working collectively and adopting a multidisciplinary approach, we can strive toward a healthier and more resilient aquatic environment for future generations.

10 Future Research Needs

It is essential to continue monitoring and studying OMPs in aquatic environments to understand their impact better and develop strategies to reduce their presence. The innovative technologies have the potential to significantly improve water treatment and protect aquatic environments from the harmful effects of organic micropollutants. Understanding their occurrence, fate, and effects is crucial for managing potential risks and developing effective strategies for their control and removal. The study of OMPs in the aquatic environment is an evolving field, and there are several areas where future research is needed to improve our understanding of these compounds and their impacts. Some of the key areas where future research is needed include:

- (a) Development of analytical methods: Identifying and quantifying OMPs in the aquatic environment can be challenging due to their low concentrations and complex matrices. Future research should focus on developing more sensitive and selective analytical methods that can accurately detect and quantify these compounds, even at trace levels.
- (b) Studies on the fate and behavior of emerging contaminants: Emerging contaminants, such as microplastics, nanomaterials, and new classes of chemicals, are gaining attention as potential threats to the aquatic environment. Future research should focus on understanding the fate and behavior of these emerging contaminants, including their transport, transformation, and potential impacts on aquatic organisms and ecosystems.
- (c) Evaluation of the effectiveness of treatment technologies: Various treatment technologies, such as advanced oxidation processes, membrane filtration, and activated carbon adsorption, are being used to remove OMPs from wastewater. Future research should evaluate the effectiveness of these technologies in

removing different classes of organic micropollutants, as well as their potential impacts on the environment and human health.

- (d) Assessment of the ecological and human health risks: OMPs can adversely affect aquatic organisms and enter the food chain, potentially impacting human health. Future research should focus on assessing the ecological and human health risks associated with exposure to these compounds, including the cumulative effects of exposure to multiple contaminants.
- (e) Development of regulatory frameworks: The regulation of OMPs in the aquatic environment is complex and varies across different countries and regions. Future research should focus on developing more effective regulatory frameworks that can manage the risks associated with these compounds and ensure the protection of the environment and human health.

Finally, future research in this field should aim to improve our understanding of organic micropollutants' fate, behavior, and impacts in the aquatic environment and develop effective strategies to manage and mitigate their risks.

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