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A Critical Review on Emerging Organic Micro Pollutants: Fate and Treatment Methods

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ABSTRACT

Emerging Organic Micropollutants (EOMPs) are a diverse group of synthetic and naturally occurring chemicals detected at trace levels in various environmental matrices, particularly water bodies. These pollutants include pharmaceuticals, personal care products, pesticides, and industrial chemicals, which pose significant risks to both human health and aquatic ecosystems due to their persistence and bioactivity. The review focuses on the sources, environmental fate, detection, and treatment methods of EOMPs, highlighting current research advancements and identifying gaps in knowledge. It also analyzes factors influencing their fate, such as chemical properties, environmental conditions, and interactions with co-contaminants. The review evaluates the effectiveness of various treatment methods, highlighting physical, chemical, and biological approaches. Despite advancements in treatment methods, significant knowledge gaps remain, particularly in understanding the long-term impacts of EOMPs and the efficiency of integrated treatment approaches. Key findings indicate that while physical, chemical, and biological treatment methods each have their advantages, no single method is universally effective. A combination of treatment technologies may offer the most promising approach for managing EOMPs. This review highlights the need for further research into sustainable treatment methods and the development of comprehensive policies to address the challenges posed by EOMPs.

Keywords: Emerging Organic Micropollutants (EOMPs), Environmental Fate, Treatment Methods, Pharmaceuticals, Bioaccumulation.

I. INTRODUCTION

1.1 Definition of Emerging Organic Micro Pollutants

Emerging Organic Micro Pollutants (EOMPs) encompass a wide rangeof natural and man-made chemicals that are not routinely assessed in the environment but have been identified in water bodies at trace levels. These pollutants includepersonal care products, pesticides, industrial chemicals, and pharmaceuticals (Mustafa et al., 2022; Shao et al., 2023). EOMPs are characterized by their low concentrations and the recent recognition of their occurrence in the environment. They are typically present in nanogram to microgram per liter concentrations, making their detection and quantification challenging (Ahmad et al., 2019; K'oreje et al., 2018).

According to K'oreje et al., 2018, the term "emerging" refers to the recent recognition of these pollutants in the environment, and the lack of monitoring and regulation.

EOMPs infiltrateinto the environment through multiple pathways, including agricultural runoff, wastewater treatment plants, and industrial effluent (Kümmerer, 2013; Topolovec et al., 2022; Wang et al., 2020). A good example are the pharmaceuticals,which are designed to produce targeted biological effects, and their occurrence in the environment may result in unanticipated outcomes, including the development of antibiotic-resistant bacteria (Kümmerer, 2013; Topolovec et al., 2022).

Triclosan and parabens (which are personal care products) are also EOMPs that have been detected in water bodies and have been associated with endocrine disruption as well as various negative health impacts (Ahmad et al., 2019; Eggen et al., 2014). Pesticides, including herbicides, insecticides, and fungicides, constitute another category of EOMPs that have been identified in aquatic environments. These compounds are designed to kill or repel pests, but their presence in the environment may result in the pollution of water sources and the buildup of harmful substances within food chains (Aktar et al., 2009; Ahmad et al., 2019).

Some Industrial chemicals like volatile organic compounds (VOCs) and polycyclic aromatic hydrocarbons (PAHs), are also EOMPs that have been detected in water bodies and have been associated with a range of detrimental health impacts, including carcinogenicity and neurotoxic effects (Kim et al., 2013; Pearce et al., 2015).

Studies have shown that EOMPs can have significant impacts on aquatic ecosystems, including changes in species composition and ecosystem function (Andersen et al., 2003; Chae &An, 2017; Schwarzenbach et al., 2006; Zhao et al., 2023). A study by Brooks et al. (2003) observed that the occurrence of pharmaceuticals and personal care products in aquatic environments may result in alterations in the behaviour and physiological functions of aquatic species.

The fate of EOMPs in the environment is determined by various factors, including their physical and chemical properties, biological processes, and environmental conditions (Ajala et al., 2022; Ng et al., 2019; Zad et al., 2018). EOMPs can undergo various transformations, including biodegradation, photodegradation, and sorption, which can affect their persistence and mobility in the natural environment (Aryal et al., 2020; Margot et al., 2015; Schwarzenbach et al., 2006).

EOMPs are a class of synthetic and naturally occurring chemicals that have been detected in water bodies at trace levels (Eregowda & Mohapatra, 2020; Luo et al., 2014). They are distinguished by their presence in minimal concentrations, recent recognition, and the lack of monitoring and regulation (Dubey et al., 2021). EOMPs include industrial chemicals, personal care products, pesticides, and, pharmaceuticals which can cause human health and environmental risks (Aryal et al., 2020; Luo et al., 2014). The fate of EOMPs in the environment is affected by various factors, are capable of undergoing transformation processes, such as photodegradation, sorption, and biodegradation (Aryal et al., 2020; Eregowda & Mohapatra, 2020; Luo et al., 2014).

1.2 Importance of Studying Emerging Organic Micro Pollutants

The increasing detection of EOMPs in the environment poses substantial threats to both human well-being and aquatic ecosystems (Muter & Bartkevics, 2020; Tan et al., 2023). EOMPs can cause various toxicological impacts, such as acute toxicity, antibiotic resistance, and endocrine disruption in aquatic life (Pal et al., 2010; Schwarzenbach et al., 2006). A better understanding of theorigins, behaviour, and treatment techniques of these pollutants is essential for formulating efficient and strategic management approaches to reduce their impact. (Pal et al., 2010).

The presence of EOMPs in drinking water sources is particularly concerning as conventional water treatment methods frequently prove inadequate in eliminating these pollutants (Deblonde et al., 2011; Kim & Zoh, 2016; Piai et al., 2020; Souza et al., 2021). A study by Ebele et al. (2020) found that personal care products and pharmaceuticals were present in groundwater, drinking water, and surface water in Lagos State, Nigeria. In Abuja, Nigeria, polybrominated diphenyl ethers (PBDEs) were detected in cow's milk and chicken eggs near municipal dumpsites, according to a study by Oloruntoba et al. (2019).EOMPs can also have significant impacts on aquatic ecosystems, including changes in species composition and ecosystem function (Muter & Bartkevics, 2020; Schwarzenbach et al., 2006; Tan et al., 2023). Ripanda et al. (2021) reported that phenolic endocrine-disrupting compounds in an urban tropical river posed ecological risks to aquatic life.The sources of EOMPs are diverse and include wastewater treatment plants, agricultural runoff, and industrial effluent (K'oreje et al., 2018; Kümmerer, 2013). Ferronato and Torretta (2019) demonstrated that improper waste management in developing countries is a major contributor to theenvironmental presence of EOMPs.

Studying EOMPs is important for several reasons. Firstly, it can help identify the sources and behaviour of these pollutants in the environment (K'oreje et al., 2018). Secondly, it can inform the development of efficient management methods to reduce their impact (Wang et al., 2020). Finally, it can provide valuable understanding regarding the toxicological impacts of EOMPs on human healthand aquatic ecosystems (Bhatt et al., 2022; K'oreje et al., 2018; Schwarzenbach et al., 2006).Egbuna et al. (2021) conducted a systematic review revealing the presence of over 250 emerging pollutants in Nigeria, encompassing pesticides, pharmaceuticals, and industrial chemicals. Additionally, K'oreje et al. (2018) detected EOMPs in wastewater stabilization ponds and the rivers receiving effluents in the Nzoia Basin, Kenya.

The importance of studying EOMPs cannot be overstated. These pollutants present considerable risks to both human healthand aquatic ecosystems (Chen et al., 2022; Yang et al., 2021; Schwarzenbach et al., 2006), and understanding their sources, fate, and treatment methods is crucial for developing effective management strategies (Luo et al., 2014; Margot et al., 2015;Schwarzenbach et al., 2006). Further research is required to determine the sources and environmental behaviour of EOMPs and to devise effective management strategies to mitigate their impact. (Dubey et al, 2021; Yang et al, 2021).

1.3 Scope and Objectives of the Review

This paper aims to give a detailed analysis of the sources, environmental fate, and treatment methods of EOMPs. It synthesizes current research findings and identifies gaps in knowledge to inform future research and policy development. The objectives include:

- Identifying the primary sources of EOMPs.
- Reviewing the transport and transformation processes of EOMPs in various environmental matrices.
- Assessing the effectiveness of different treatment methods for EOMPs.
- Discussing future perspectives and challenges in managing EOMPs.

II. SOURCES AND TYPES OF EMERGING ORGANIC MICRO POLLUTANTS

As shown in Figure 1, the sources of EOMPs can broadly be classified into:

1. Industrial Sources

Industrial activities are significant contributors to the presence of emerging organic micro pollutants (EOMPs) in the environment (Gautam, K., & Anbumani, 2020; Jiang et al., 2013; Verlicchi et al., 2010). These activities release various organic pollutants, including solvents, plasticizers, and surfactants, into the environment. These pollutants often enter water bodies through effluent discharges and improper waste disposal practices (Vodyanitskii & Yakovlev, 2016). The effluents from manufacturing processes and the disposal of industrial waste without adequate treatment lead to the contamination of water resources with these harmful substances (Pal et al., 2010).Industrial solvents, such as trichloroethylene and toluene, are widely used in manufacturing processes for cleaning and degreasing metal parts, electronics, and textiles. These solvents can easily volatilize and contaminate air, soil, and water. Improper discharge of these substances can result in their persistence in the environment, thereby endangering human health (Chen et al., 2021; Ducatman, 2004).

Plasticizers (like phthalates) are employedto enhance the flexibility and durability of plastics. These chemicals are prevalent in products like PVC pipes, vinyl flooring, and various consumer goods (Jamarani et al., 2018; Ma et al., 2020; Rahman & Brazel, 2004). Phthalates can leach out of these products over time, contaminating soil and water. Their persistence in the environment and potential endocrine-disrupting properties make them a significant concern (Dueñas-Moreno et al., 2022; Sajid et al., 2016).Surfactants, such as nonylphenol ethoxylates, are used in industrial cleaning agents, detergents, and emulsifiers (Jardak et al., 2016). These substances can break down into more toxic compounds and persist in aquatic environments (Sharma et al., 2018). The discharge of industrial effluents containing surfactants can lead to the contamination of water bodies, affecting aquatic organisms and ecosystems (Akpor et al., 2014; Kanu & Achi, 2011).

In addition to solvents, plasticizers, and surfactants, industrial activities also release additional organic pollutants, such as flame retardants, dyes, and pharmaceuticals (Chen et al., 2021; Ducatman, 2004; Jamarani et al., 2018). Flame retardants, like PBDEs, are used in electronics, textiles, and construction materials to reduce flammability (Oloruntoba et al., 2019). These chemicals can pose long-term risks when they accumulate in living organisms and the environment (Oloruntoba et al., 2019).Dyes and pigments used in textile manufacturing and other industries can also contribute to EOMPs (Akpor et al., 2014; Jamarani et al., 2018). These substances often contain complex chemical structures that are resistant to degradation, leading to their persistence in the environment (Jardak et al., 2016). Discharging effluents containing dyes can lead to the pollution of water bodies, which in turn impacts aquatic life and may eventually enter the food chain. (Al-Tohamy et al., 2022; Dutta et al., 2024).Pharmaceuticals like hormones and antibiotics,can contaminate the environment due to improper disposal and effluent discharges. These substances may negatively impact aquatic organisms by causing endocrine disruption and contributing to the development of antibiotic-resistant bacteria (Pal et al., 2022).

2. Agricultural Sources

The agricultural use of herbicides, pesticides, and veterinary pharmaceuticals contributes significantly to this issue (Sánchez-Bayo, 2011; Weldeslassie et al., 2018). These substances have the potential to runoff into surface water or leach into groundwater, leading to widespread contamination. The application of these chemicals in agriculture, intended to protect crops and livestock, inadvertently impacts surrounding water bodies and soil, thereby contributing to the persistence of these pollutants in the ecosystem (Kümmerer, 2013; Pal et al., 2010). Herbicides, fungicides,and insecticidesare used extensively to protect crops from pests, weeds, and diseases. However, these chemicals can persist in the environment and be transported through runoff and leaching, contaminating soil and water (Pal et al., 2010). Atrazine, glyphosate, and neonicotinoids, have been found in groundwater and surface water, posing potential threats to non-target organisms and ecosystems.Insecticides, like pyrethroidsand organophosphates, are used to control insect pests in agriculture (Wan et al., 2021). These chemicals can be highly toxic to aquatic life, birds, and beneficial insects like bees. Their presence can disrupt the ecosystem and reduce biodiversity (Pal et al., 2010; Székács et al., 2015; Wan et al., 2021).

Herbicides, including glyphosate and 2,4-D, are used inagricultural weedcontrol(Boutin, 2020; de Castro Marcato et al., 2017; Mehdizadeh et al., 2021). These chemicals have the potential to remain in soil and water, thereby impacting non-target plants and aquatic organisms. The extensive application of herbicides has resulted in the emergence of herbicide-resistant weeds, which complicates pest management strategies (de Castro Marcato et al., 2017; Mehdizadeh et al., 2021).Fungicides, used to control fungal diseases in crops, can also contribute to EOMPs. These chemicals can persist in soil and water, affecting non-target organisms and and possibly infiltrating the food chain. The use of fungicides, such as azoles and strobilurins,may result in the emergence of resistant fungal strains, complicating disease management efforts (Corkley et al., 2022; Hollomon, 2015; Lucas et al., 2015).

Veterinary pharmaceuticals, including antibiotics, antiparasitics, and hormones, are used in livestock production to treat and prevent diseases and promote growth (Atta et al., 2022; Bártíková et al., 2016). These substances can enter the environment through manure and urine, which are often applied to agricultural fields as fertilizer (Obimakinde et al., 2017). The presence of veterinary pharmaceuticals in soil and water can affect microbial communities, promote antibiotic resistance, and disrupt endocrine systems in wildlife (Lee et al., 2007; Bean et al., 2024).The use of biosolids and animal manure as fertilizers in agriculture can also contribute to the presence of EOMPs. Biosolids, which are produced from treated sewage sludge, may contain a variety of organic pollutants, such as personal care products, industrial chemicals,and pharmaceuticals(Wan et al., 2021). When applied to agricultural fields, these substances can runoff into surface water or leach into groundwater, leading to contamination (de Castro Marcato et al., 2017; Mehdizadeh et al., 2021).

In addition to chemical inputs, agricultural practices such as irrigation and drainage may affect the mobility and fate of EOMPs (Wan et al., 2021). Irrigation with contaminated water can introduce EOMPs into agricultural fields, where they can accumulate in soil and crops. Drainage systems can facilitate the movement of EOMPs from agricultural fields to adjacent water bodies, thereby heightening the risk of contamination (Székács et al., 2015).

3. **Domestic Sources**

Household products, including personal care products, pharmaceuticalsand cleaning agents, are major sources of EOMPs (K'oreje et al., 2018; Pegu et al., 2023). These substances typically enter the environment through sewage and wastewater treatment plants. Despite treatment processes, many of these chemicals are not completely removed and end up in water bodies. The extensive daily use of these products leads to a continuous influx of EOMPs into wastewater systems, which eventually impacts the environment (Heberer, 2002).

Pharmaceuticals used for human and veterinary medicine are a major source of EOMPs (Mustafa et al., 2022; Shao et al., 2023). These substances include antibiotics, analgesics, hormones, and other therapeutic agents. Pharmaceuticals can enter the environment through excretion, improper disposal, and discharge from wastewater treatment facilities. Their presence in water bodies can affect aquatic organisms, promoting antibiotic resistance and disrupting endocrine systems (Shao et al., 2023).Personal care products, such as preservatives, fragrances, and UV filtersare widely used in toiletries, cosmetics, and household products (Pegu et al., 2023). These chemicals can enter the environment through washing and bathing, potentially bypassing wastewater treatment facilities and contaminating water bodies. Some personal care products, like triclosan and parabens, have been found in groundwater, surface water,and drinking water, raising concerns about their potential health impacts (Pegu et al., 2023).

Cleaning agents, including detergents, disinfectants, and surfactants, are used extensively in households (K'oreje et al., 2018). These substances can enter the environment through wastewater, where they can persist and accumulate in aquatic ecosystems. Surfactants, such as alkylphenol ethoxylates, can break down into more toxic compounds, affecting aquatic life and water quality (Kovarova et al., 2013).In addition to pharmaceuticals, personal care products, and cleaning agents, other household products, such as paints, solvents, and pesticides, can also contribute to EOMPs (K'oreje et al., 2018). The improper disposal of these products, such as pouring them down the drain or discarding them in household trash, can lead to contamination of wastewater and the environment (K'oreje et al., 2018).The use of synthetic fragrances in personal care products, air fresheners, and cleaning agents can introduce a variety of VOCs into the environment (Rádis-Baptista, 2023; Steinemann, 2015). These chemicals can persist in indoor and outdoor air, contributing to air pollution and potential health risks (Steinemann, 2009).

In addition to domestic wastewater, stormwater runoff from urban areas can also contribute to the presence of EOMPs. Stormwater can carry pollutants from roads, roofs, and other surfaces into water bodies, including organic pollutants from vehicles, building materials, and household products (Aryal et al., 2010; Müller et al., 2020).

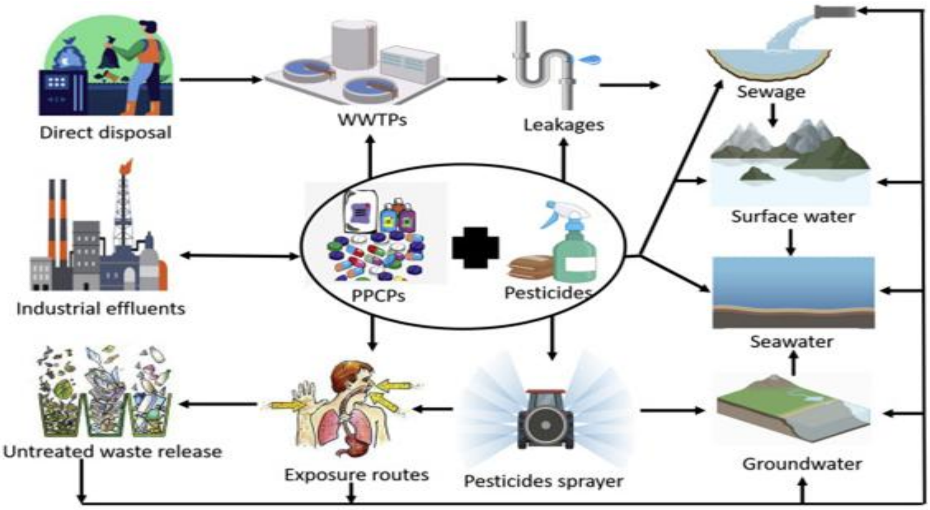

Figure 1: Sources, Transport, and Exposure Routes of EOMPS and Pesticides in Various Water Systems.Reproduced from Okoye et al. (2022).

2.1 Classification of EOMPs

EOMPs can be broadly categorized into the following types:

i. Pharmaceuticals (e.g., antibiotics, analgesics) (Bean et al., 2024; Ebele et al., 2020; Jelic et al., 2015)
ii. Personal care products (e.g.UV filters, fragrances) (Brausch & Rand, 2011; Manová et al., 2013)
iii. Pesticides (e.g., insecticides, herbicides) (Pegu et al., 2023)
iv. Industrial chemicals (e.g., plasticizers, flame retardants) (Andresen et al., 2004; Andresen & Bester, 2006)

Pharmaceuticals: This category includes substances such as antibiotics, analgesics, hormones, and other therapeutic agents (Bean et al., 2024; Ebele et al., 2020). Pharmaceuticals are used for medical treatments in animals and humans and often enter the environment throughimproper disposal, excretion, and discharge from wastewater treatment facilities (Ebele et al., 2020). Examples of pharmaceuticals found in the environment include antibiotics like ciprofloxacin, analgesics like ibuprofen, and hormones like estradiol. These substances may negatively impact aquatic organisms, promoting antibiotic resistance and disrupting endocrine systems (Jelic et al., 2015).

Personal Care Products: This group comprises UV filters, fragrances,preservatives, and other substances used in cosmetics, toiletries, and household products. These chemicals are released into the environment through daily usage and washing off, entering water bodies through wastewater systems (Manová et al., 2013). Examples of personal care products found in the environment include fragrances like musk ketone, UV filters like octocrylene, and preservatives like parabens. These substances can affect aquatic organisms and potentially impact human health through water contamination (Brausch and Rand, 2011).

Pesticides: In agriculture,insecticides, herbicides, and pesticides, fungicides are used extensively to protect crops against diseases, weeds, and pests(Pegu et al., 2023). These chemicals can persist in the environment and be transported through runoff and leaching, contaminating soil and water. Surface water and groundwater have been found to contain pesticides like glyphosate, atrazine, and neonicotinoids, which pose risks to non-target organisms and ecosystems (Stehle & Schulz, 2015).

Industrial Chemicals: This category encompasses a variety of substances such as plasticizers, flame retardants, and solvents used in manufacturing processes (Andresen et al., 2004; Andresen & Bester, 2006). These chemicals can enter the environment through industrial effluents and improper waste disposal, leading to significant environmental contamination. Examples of industrial chemicals include phthalates used as plasticizers, PBDEs used as flame retardants, and trichloroethylene used as a solvent (Rahman et al., 2001). These substances can remain in the environment and build up in living organisms (Andresen et al., 2004).

III. ENVIRONMENTAL FATE OF EOMPS

The environmental fate of EOMPs is determined by a complex interplay of release mechanisms, transport dynamics and transformation processes, and their persistence and bioaccumulation in different environmental matrices (Aryal et al., 2020; Dubey et al., 2021; Zad et al., 2018).

3.1 Mechanisms of EOMPs Release into the Environment

EOMPs are released into the environment through various pathways, including industrial discharges, agricultural runoff, and domestic sewage (Dueñas-Moreno et al., 2022). Industrial activities discharge a range of organic pollutants such as solvents, plasticizers, and surfactants into water bodies through improper waste disposal and effluent discharges (Pal et al., 2010). Also, the use ofherbicides, pesticides, and veterinary pharmaceuticals contributes to the presence of EOMPs, which can runoff into surface water or leach into groundwater (Kümmerer, 2013; Pal et al., 2010).

Domestic sources, including household products like personal care products, pharmaceuticals, and cleaning agents, also add to EOMPs (Pal et al., 2010). These pollutants typically enter the environment through sewage and wastewater treatment facilities (Dueñas-Moreno et al., 2022; Zad et al., 2018). Inadequate treatment of wastewater exacerbates the presence of these pollutants in aquatic environments, as routine treatment processes often fail to completely eliminate them.In novel wastewater treatment plants (WWTPs), while energy consumption is reduced, the removal efficiency of EOMPs varies depending on the technology used for organic carbon preconcentration (K'oreje et al., 2018). Configurations based on high-rate activated sludge (HRAS) with or without the incorporation of a rotating belt filter (RBF), or chemically enhanced primary treatment (CEPT), succeeded by a partial nitritation-anammox (PN-AMX) unit, show different efficiencies in removing EOMPs (Taboada-Santos, 2019). These innovative configurations may result in removal efficiencies for EOMPs from wastewater that are either comparable to or lower than those achieved by conventional WWTPs.Additionally, the concentration of hydrophobic EOMPs in the digested sludge can vary significantly across different configurations (Taboada-Santos, 2019).

3.2 Transport and Transformation Processes in Various Environmental Matrices

Once released into the environment, EOMPs can undergo various chemical, biological, and physicaltransformations that influence their persistence and mobility. These processes include adsorption, hydrolysis, microbial degradation, and photodegradation (Guo et al., 2023; Hermes et al., 2018; Jiang et al., 2013).

Adsorption: EOMPs can accumulate on sedimentand soil particles, which affects their transport and bioavailability. Hydrophobic EOMPs, in particular, tend to adsorb strongly to organic matter in sediments and soils (Boxall et al., 2004; Fard et al., 2017; Mailler et al., 2016).

Photodegradation: Exposure to sunlight can cause photodegradation of certain EOMPs, transforming them into substances that pose a reduced risk or are less hazardous. This process is influenced by the chemical structure of the EOMP and environmental conditions such as sunlight intensity and presence of photo-sensitizers (Boxall et al., 2004; Pal et al., 2010).

Hydrolysis: Some EOMPs can undergo hydrolysis, a chemical reaction with water that breaks down the pollutants into simpler compounds. The rate of hydrolysis depends on the chemical properties of the EOMP and the pH and temperature of the water (Boxall et al., 2004; Mailler et al., 2016).

Microbial Degradation: Microorganisms can degrade EOMPs through metabolic processes. This biodegradation can occur in soil, water, and sediments, and the efficiency depends on the presence and activity of specific microbial communities, as well as environmental conditions (Ebele et al., 2020; Pal et al., 2010).

The transport of EOMPs is influenced by their solubility, volatility, and affinity for organic matter (Ebele et al., 2020). Soluble EOMPs can readily move with water, while volatile compounds can enter the atmosphere and be transported over long distances. EOMPs with a high affinity for organic matter are likely to accumulate in soils and sediments (Ebele et al., 2020).

3.3 Persistence and Bioaccumulation

Due to their chemical stability, many EOMPs persist in the environment and can bioaccumulate in aquatic organisms (Desiante et al., 2021; Filote et al., 2021). Persistence refers to the resistance of EOMPs to degradation processes, resulting in long-term environmental presence (Desiante et al., 2021). This persistence is often due to the molecular structure of EOMPs, which makes them resistant to natural breakdown mechanisms (Desiante et al., 2021; Filote et al., 2021).Bioaccumulation occurs when EOMPs are absorbed by organisms at a rate faster than they are metabolized or excreted (Desiante et al., 2021). This can result in elevated levels of these contaminants within organisms compared to their external environment (Desiante et al., 2021; Filote et al., 2021). Persistent EOMPs can build up in the tissues of aquatic species, and through the process of biomagnification, their concentrations can increase up the food chain. This creates substantial health risks for predators and humans consuming contaminated fish and other aquatic species (Boxall et al., 2004; Jelic et al., 2015).

The presence of hydrophobic EOMPs in the sludge of WWTPs is particularly concerning, given that these contaminants may be reintroduced into the ecosystem through the use of sludge as agricultural fertilizer (Dubey et al., 2021). Novel WWTP configurations, such as those based on HRAS, can lead to lower concentrations of hydrophobic EOMPs in digested sludge compared to conventional configurations, making them a more efficient alternative for minimizing environmental contamination (Dubey et al., 2021; Taboada-Santos et al., 2020).

3.4 Factors Influencing the Fate of EOMPs

The behaviour of EOMPsin the environment is a complex interplay of numerous variables. These variables, outlined in Table 1, determine the persistence, dispersal, and potential effects of EOMPs on human healthand ecosystems (Aryal et al., 2020; Dubey et al., 2021; Zad et al., 2018). Key determinants affecting the fate of EOMPs include their chemical properties, environmental settings, and the existence of additional pollutants.

Table 1: Factors Affecting the Fate of EOMPs

Factors	Description
Chemical Properties of the EOMPs	i. **Solubility:** Influences mobility and bioavailability. Highly soluble EOMPs are more likely to dissolve in water. i. **Volatility:** Determines potential for air dispersion and long-range transport. i. **Hydrophobicity:** Leads to bioaccumulation in the food chain. v. **Chemical Stability:** Determines resistance to degradation processes, influencing persistence in the environment.
Environmental Conditions	i. **Temperature:** Affects chemical reactions and biological processes. Higher temperatures can enhance degradation or increase volatility. i. **pH:** Influences ionization state, solubility, and reactivity of EOMPs. i. **Sunlight:** Can induce photolytic degradation depending on wavelength and intensity. v. **Redox Conditions:** Influence transformation through oxidizing or reducing agents.
Presence of Other Pollutants	i. **Co-contaminants:** Can inhibit microbial degradation, increasing persistence. i. **Complex Formation:** Alters solubility, mobility, and toxicity. i. **Competition for Sorption Sites:** Influences distribution and mobility through competition with other pollutants for sorption sites.

3.4.1 Chemical Properties

The intrinsic chemical properties of EOMPs significantly influence their environmental behaviour. These properties include:

Solubility: The solubility of an EOMP in water determines its mobility and bioavailability. Highly soluble compounds are more likely to dissolve in water and be transported through aquatic systems, whereas less soluble compounds may accumulate in sediments or soils (Boxall et al., 2004; Mailler et al., 2016).

Volatility: Volatile EOMPs can evaporate into the atmosphere, leading to air dispersion and potential long-range transport. This process can result in the widespread distribution of EOMPs far from their original sources (Pal et al., 2010).

Hydrophobicity: Hydrophobic (water-repelling) EOMPs tend to partition into organic matter, such as sediments and biota. This can lead to bioaccumulation in the food chain, posing risks to humans and wildlife (Boxall et al., 2004).

Chemical Stability: The stability of an EOMP determines its resistance to degradation processes such asphotolysis, microbial degradation, and hydrolysis. Stable EOMPs can remain in the environment for extended durations, increasing the likelihood of chronic exposure (Mehdizadeh et al. 2021; Pal et al., 2010).

3.4.2 Environmental Conditions

The conditions of the Environmentsignificantly influence the fate of EOMPs, influencing their behaviour and transformation. Temperature is one of these significant factors. It influences the rates of chemical reactions and biological processes (Mehdizadeh et al. 2021). Higher temperatures can enhance the degradation of some EOMPs, making them break down more quickly and reducing their persistence in the environment. Conversely, other EOMPs may become more volatile at elevated temperatures, increasing their tendency to evaporate and potentially spreading their impact over larger areas (Boxall et al., 2004).The pH of the environment also affects the fate of EOMPs. The ionization state of EOMPs can change depending on the pH, which alters their solubility and reactivity. Ng et al. (2019) reported that certain EOMPs can exhibit increased solubility under acidic or basic conditions, affecting their mobility and bioavailability. This means that changes in pH can influence how EOMPs move through the environment and how readily they can be taken up by organisms (Pal et al., 2010).

Sunlight exposure is another critical factor affecting EOMP fate. Photolytic degradation, induced by sunlight, can break down certain EOMPs (Mustafa et al., 2022). The effectiveness of this process is contingent upon the intensity and wavelength of the light, as well as the presence of photosensitizers that facilitate the breakdown of these pollutants. This means that sunlight can help mitigate the presence of some EOMPs in the environment by promoting their degradation (Boxall et al., 2004).Redox conditions, or the presence of oxidizing or reducing agents, also play a significant role. These conditions can influence the chemical structure and reactivity of EOMPs, affecting their transformation and potential toxicity (Okoye et al., 2022; Zad et al., 2018). For example, in environments with strong oxidizing conditions, certain EOMPs might break down more readily, whereas reducing conditions might stabilize others. Understanding the redox conditions in a given environment is essential for predicting the behaviour and impact of EOMPs (Pal et al., 2010).

3.4.3 Presence of Other Pollutants

The interaction between EOMPs and other pollutants can modify their fate in the environment. These interactions among pollutants may either enhance or hinder each other's effects, contingent upon their specific characteristics.Co-contaminants play a significant role in this dynamic (Zad et al., 2018). The presence of other organic or inorganic pollutants can influence the sorption, desorption, and degradation of EOMPs. Research has shown that heavy metals can impede the microbial degradation of EOMPs, resulting in their prolonged environmental persistence (Boxall et al., 2004). This suggests that heavy metals and EOMPs can interact in ways that complicate their removal and exacerbate their environmental impact (Ripanda et al., 2021).

Complex formation is another crucial interaction. EOMPs can form complexes with other chemicals, which alters their solubility, mobility, and bioavailability (Besha et al., 2020). These complexes can be more or less toxic than the parent EOMPs, thereby impacting their overall environmental risk. According to Besha et al. (2020) and Pal et al. (2010), the formation of a complex may make an EOMP more soluble and mobile, increasing its potential to spread through the environment and have a widerimpact on various organisms (Besha et al., 2020; Pal et al., 2010).

Competition for sorption sites is also an important factor. In soils and sediments, EOMPs may compete with other pollutants for sorption sites on organic matter and minerals. This competition can influence the distribution and mobility of EOMPs, thereby affecting their environmental fate. For example, if EOMPs and other contaminants are vying for the same sorption sites, the presence of one can affect the sorption behaviour of the other, potentially leading to increased mobility and bioavailability of EOMPs (Boxall et al., 2004; Cova et al., 2018).

IV. TREATMENT METHODS FOR EOMPS

The treatment of EOMPs is a crucial component of environmental management due to their enduring nature and potential detrimental impacts. Various treatment methods are employed to remove or degrade EOMPs from waterwater and waste (Al-Tohamy et al., 2022; Filote et al., 2021; Jiang et al., 2013; Luo et al., 2014). These techniques are broadly categorized into biological,chemical, and physicaltreatments, each with its own advantages and limitations (see Table 2).

4.1 Physical Treatment Methods

Physical methods involve the removal of EOMPs based on their physical properties, without altering their chemical structure significantly.

4.1.1 Filtration

Filtration techniques such as microfiltration, ultrafiltration, and nanofiltration effectively remove particulate-bound and dissolved EOMPs from water. Microfiltration typically removes larger particles, while ultrafiltration and nanofiltration target smaller particles and dissolved substances. These methods rely on membrane technologies that selectively allow water molecules to pass through while retaining contaminants. Challenges include membrane fouling due to organic matter accumulation, which reduces filtration efficiency and necessitates frequent cleaning or replacement (which increases operational costs) (Khan et al., 2022; Virkutyte & Varma, 2010).

4.1.2 Adsorption

Adsorption processes utilize materials like activated carbon, biochar, and synthetic resins to attract and bind EOMPs from water onto their surfaces. These materials have high surface areas that can adsorb a variety of organic pollutants. Due to its extensive surface area and porous structure, activated carbon is widely used but can be expensive to regenerate. Biochar, derived from biomass pyrolysis, shows promise for its renewability and effectiveness in adsorbing a range of organic pollutants, though optimization of production and application methods is ongoing (Liu et al., 2018; Virkutyte & Varma, 2010).

4.1.3 Membrane Technologies

Technologies utilizing membranes, including reverse osmosis (RO) and forward osmosis (FO) offer high removal efficiencies for EOMPs through physical sieving and selective permeation. RO uses pressure to force water through a semi-permeable membrane, effectively rejecting EOMPs based on size and charge (Oller et al., 2018). FO, a newer approach, uses osmotic pressure gradients to draw water through a membrane, potentially reducing energy consumption compared to traditional RO but requiring further development for widespread application. (Hube et al., 2021; Radjenović et al., 2008; Snyder et al., 2007).

4.1.4 Advantages and Limitations

Physical treatment methods are advantageous for their high removal efficiencies and versatility in handling a wide range of EOMPs. However, they often require high operational costs and regular maintenance to prevent membrane fouling and ensure efficiency. The scalability and sustainability of these methods can be limited by the need for energy and frequent replacement or regeneration of materials (Radjenović et al., 2008; Snyder et al., 2007).

4.2 Chemical Treatment Methods

Chemical treatment methods involve altering the chemical structure of EOMPs through chemical reactions to facilitate their removal or degradation into less harmful substances.

4.2.1 Advanced Oxidation Processes (AOPs)

Advanced Oxidation Processes (AOPs) harness highly reactive hydroxyl radicals to break down EOMPs into simpler, less toxic compounds. Techniques such asFenton reactions, UV/H_2O_2 , and ozonationare effective but require careful control to minimize the formation of harmful by-products. Innovation focuses on enhancing process efficiency, reducing energy consumption, and exploring novel catalysts or additives to improve degradation kinetics and selectivity. However, AOPs can be costly and require careful handling of oxidants and reaction conditions to avoid the formation of harmful by-products (Oller et al., 2018).

4.2.2 Photodegradation

Photodegradation utilizes UV irradiation to degrade EOMPs by inducing photochemical reactions that cleave chemical bonds and reduce molecular complexity. This method is effective for specific pollutants but may require long exposure times and can be affected by water quality parameters such as the presence of natural organic matter and turbidity, and variability in pollutant sensitivity to light. The effectiveness of photodegradation is dependent on the wavelength and intensity of the UV light used (Andreozzi et al., 2003). Innovations aim to improve reactor design, enhance UV penetration, and integrate synergistic processes to optimize the efficiency of degradation processes while reducing energy consumption.

4.2.3 Chemical Precipitation

Chemical precipitation involves adding chemicals that react with EOMPs to form insoluble precipitates, which can be separated from water by filtration or settling. While effective for certain metals and inorganic pollutants, its applicability to organic pollutants is limited due to the complex nature of EOMPs and the potential for secondary pollution from residual chemicals or precipitates. The process can produce sludge that requires proper disposal and may not be suitable for treating all types of EOMPs (Snyder et al., 2007; Vogelsang et al., 2006).

4.2.4 Advantages and Limitations

Chemical treatment methods are effective for degrading complex organic pollutants. However, they can produce by-products that may need further treatment and require careful control of reaction conditions. The costs associated with chemical reagents and the management of by-products can also be significant (Oller et al., 2018; Souza et al., 2021). Innovations focus on developing eco-friendly chemicals, optimizing dosing strategies, and integrating treatment trains to enhance overall process efficiency and sustainability.

4.3 Biological Treatment Methods

Biological methods utilize living organisms or their metabolic processes to degrade or remove EOMPs from water/wastewater and the environment.

4.3.1 Biodegradation

Biodegradation employs microorganisms to enzymatically break down EOMPs into simpler, less harmful substances. While environmentally friendly and sustainable, its application is limited by the biodegradability and bioavailability of specific pollutants, as well as factors influencing microbial activity (e.g., temperature, pH, nutrient availability). Some EOMPs are resistant to microbial degradation, which limits the effectiveness of this approach (Filote et al., 2021; Jelic et al., 2015; Margot et al., 2015; Kanaujiya et al., 2019). Innovations focus on microbial consortia engineering, bioreactor design optimization, and exploring genetic modifications to enhance degradation capabilities and broaden substrate specificity.

4.3.2 Phytoremediation

Phytoremediation utilizes plants to uptake, accumulate, and metabolize EOMPs through roots or aerial parts. This method offers cost-effective, aesthetically pleasing, and sustainable solutions, particularly for contaminants in surface water or shallow groundwater. Challenges include selecting appropriate plant species based on pollutant uptake capacity and environmental conditions, as well as optimizing system design to enhance contaminant removal efficiency and minimize ecological impacts (Filote et al., 2021; Jelic et al., 2015).

4.3.3 Constructed Wetlands

Kaur et al., 2020 describe constructed wetlands as engineered systems that replicate natural wetland environments to manage wastewater and stormwater runoff. These systems leverage vegetation, soil, and microbial populations to eliminate pollutants through mechanisms including adsorption, biodegradation, and precipitation. While effective for certain EOMPs, their performance depends on hydraulic residence time, vegetation type, substrate composition, and climate conditions. Innovations focus on enhancing treatment efficiency, integrating hybrid systems (e.g., integrated constructed wetlands and membrane bioreactors), and exploring plant-microbe interactions to optimize nutrient cycling and contaminant removal (Tahindrazana, 2019).

4.3.4 Advantages and Limitations

Biological treatment methods offer sustainable, eco-friendly approaches to managing EOMPs but may be slower and less effective than physical or chemical methods for certain pollutants. Innovations in molecular biology, biotechnology, and ecological engineering are essential for advancing biological treatment technologies, improving process efficiency, and expanding applicability across diverse environmental settings. The effectiveness of biological treatments can be affected by environmental conditions including pH levels, the presence of other pollutants, and temperature(Desiante et al., 2021; Dutta et al., 2024).

Table 2: Treatment Methods for EOMPs

Method	Advantages	Limitations	Possible Further Research Areas
Physical Methods			
Filtration	High removal efficiency for particulate-bound and dissolved EOMPs.	Membrane fouling reduces efficiency and requires frequent cleaning or replacement, increasing operational costs.	Development of fouling-resistant membranes, optimization of cleaning protocols.
Adsorption	High surface area materials like activated carbon and biochar effectively adsorb various organic pollutants.	Activated carbon is expensive to regenerate; biochar production and application methods need optimization.	Research on renewable and cost-effective adsorbents, optimization of biochar production.
Membrane Technologies	High removal efficiencies through physical sieving and selective permeation (e.g., RO and FO).	High energy consumption (especially RO), further development needed for widespread FO application.	Enhancing energy efficiency, development of scalable FO systems.
Chemical Methods			
Advanced	Effective for degrading	Production of potentially	Development of eco-

Oxidation Processes (AOPs)	complex organic pollutants	harmful by-products, high operational costs	friendly oxidants, optimization of reaction conditions
Chemical Precipitation	Effective for certain metals and inorganic pollutants	Limited applicability to organic pollutants, sludge disposal issues	Innovative precipitating agents, integration with other treatment methods
Biological Methods			
Biodegradation	Environmentally friendly, sustainable	Limited by biodegradability and bioavailability of specific pollutants	Engineering microbial consortia, genetic modifications to enhance degradation
Phytoremediation	Cost-effective, aesthetically pleasing, sustainable solutions	Selection of appropriate plant species, optimization of system design	Enhancing plant uptake efficiency, minimizing ecological impacts
Constructed Wetlands	Mimics natural ecosystems, effective for certain EOMPs	Performance dependent on hydraulic residence time, vegetation type, substrate composition	Integration of hybrid systems, exploring plant-microbe interactions

V. CHALLENGES AND FUTURE PERSPECTIVES

Addressing the challenges posed by Emerging Organic Micropollutants Development of eco-friendly oxidants, optimization of reaction conditions (EOMPs) requires navigating complex scientific, technological, and regulatory landscapes. As our understanding of these pollutants deepens, so too must our approaches to treatment, regulation, and research.

Despite significant progress, several gaps persist in our understanding and management of Emerging Organic Micropollutants (EOMPs). Many EOMPs remain unidentified or poorly characterized, hindering the development of targeted treatment strategies. A critical area of study is the environmental behaviour and transport of EOMPs; understanding their pathways and behaviour in different environmental matrices, such as sediment, soil, and aquatic systems, is essential for predicting their impact and developing effective remediation techniques(Schwarzenbach et al., 2006).

Furthermore, there is limited knowledge about the prolonged consequences and ecotoxicology of EOMPs on human health and ecosystems, particularly at low concentrations or when combined with other pollutants. The rapid evolution of chemicals and their metabolites presents additional challenges, as emerging contaminants often outpace existing monitoring and treatment technologies, necessitating adaptive approaches(Al-Tohamy et al., 2022). Finally, developing cost-effective, scalable technologies that integrate multiple treatment methods—physical, chemical, and biological—for comprehensive EOMP removal remains a significant challenge.

5.1 Technological and Regulatory Challenges

From a technological perspective, energy efficiency is a significant concern. Many treatment technologies, such as membrane processes and advanced oxidation, require substantial energy inputs, which drive operational costs and have notable environmental impacts (Hube et al, 2021). Additionally, material sustainability is a critical area of focus. Developing sustainable materials for adsorption and membrane technologies that are both cost-effective and eco-friendly remains a priority. This ensures that technological solutions do not contribute to further environmental degradation. Another vital aspect is the enhancement of monitoring and detection capabilities. Improving the sensitivity and specificity of monitoring technologies is crucial to detect low levels of EOMPs in complex matrices, which is essential for effective risk assessment and management (Muter & Bartkevics, 2020).

On the regulatory side, one of the primary challenges is the lagging standards. Current regulations often fall behind scientific advancements, necessitating timely updates to include new EOMPs and emerging contaminants. This lag can hinder effective management and mitigation efforts. Interdisciplinary collaboration is also essential for robust regulatory frameworks.

Bridging gaps between scientific research, policy development, and public health implications is crucial to ensure that regulations are based on the latest scientific evidence and address real-world health risks (Richardson & Razzaque, 2011). Furthermore, achieving global harmonization in EOMP regulation and management approaches is challenging but necessary. International consensus is needed to ensure consistency and effectiveness across borders, as environmental issues and contaminants often do not respect national boundaries.

5.2 Future Research Directions

Future research efforts should focus on advancing our understanding and capabilities in several key areas. One critical area is the development of integrated treatment systems. By creating hybrid treatment systems that combine physical, chemical, and biological methods, we can synergistically enhance EOMP removal efficiency. This approach leverages the strengths of each method to provide a more comprehensive and effective solution for managing EOMPs.

Exploring nano-enabled technologies represents a potentially valuable research avenue. Nanotechnology offers significant potential for the targeted removal and degradation of EOMPs. However, it is essential to consider and mitigate any potential risks to human and environmentalhealth posed by these technologies. Ensuring that nano-enabled solutions are safe and effective is crucial for their successful implementation.

Advancing predictive modeling tools is also a key focus for future research. By developing sophisticated models to simulate EOMP fate, transport, and transformation under varying environmental conditions and treatment scenarios, we can better predict and manage the behaviour of these pollutants. This knowledge will enable more efficient approaches for risk assessment and management.

Finally, comprehensive ecotoxicological studies are essential to assess the prolonged impact of EOMPs on terrestrial and aquatic ecosystems. Understanding how EOMPs interact with other stressors and affect various organisms is essential for advancing accurate risk assessments and informing regulatory decisions. Conducting thorough research in this area will help protect ecosystem health and ensure the sustainability of our natural resources.

5.3 Policy and Regulatory Implications

Effective policy and regulatory frameworks are essential for managing EOMPs and protecting environmental and human health.Strengthening monitoring and reporting systems is a critical component of these frameworks. By implementing robust monitoring programs to track EOMP concentrations in water bodies, authorities can enable early detection and prompt response to emerging contaminants (Sanganyado, 2022). This proactive approach helps mitigate potential risks before they escalate, thereby safeguarding the health of the public and water resources.

Risk-based management is another vital aspect of effective policy frameworks. Adopting risk-based approaches allows for prioritizing EOMP mitigation efforts based on potential harm and exposure pathways. This targeted strategy ensures that resources are allocated efficiently, addressing the most significant threats first and minimizing overall risk.

Incentivizing innovation is crucial for advancing the development of eco-friendly and economically efficient EOMP treatment methods. Providing incentives and funding mechanisms to support innovation and research in this field encourage the creation of innovative solutions (Sanganyado, 2022). These advancements can significantly improve the effectiveness and efficiency of EOMP management, leading to better environmental and health outcomes.

Public awareness and engagement are essential for fostering informed decision-making and support for regulatory measures. Enhancing public awareness of EOMPs and their impacts helps communities understand the importance of regulations and their role in protecting human healthand the environment. Engaging the public in the regulatory process ensures that policies are transparent, widely accepted, and effectively implemented (Richardson & Razzaque, 2011).

VI. CONCLUSION

This review presents a thorough overview of the sources, environmental persistence, and treatment methods of EOMPs. Personal care products, industrial chemicals, pesticides, and pharmaceuticals enter ecosystems through various pathways, contributing to environmental contamination. Their persistence and ability to bioaccumulate pose risks to marine species and could potentially impact human health through dietary consumption. Effective management strategies involve understanding the chemical and environmental factors influencing their fate, coupled with the advancement in innovative treatment technologies.

Physical methods such as filtration and adsorption offer high removal efficiencies, though they require careful management to avoid secondary pollution. Chemical treatments, including Advanced Oxidation Processes (AOPs) and chemical precipitation, show promise but necessitate optimization to minimize by-products and operational costs. Biological treatments, such as biodegradation and phytoremediation, provide sustainable alternatives but require consideration of environmental conditions and pollutant specificity.

Challenges remain in pollutant identification, understanding long-term ecological impacts, and integrating diverse treatment technologies. Future studies should aim to develop integrated treatment systems, advancing predictive modeling of EOMP behaviour, and enhancing regulatory frameworks to address emerging contaminants effectively.

Conflict of Interest Statement

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