International Journal of Biosciences | IJB |
ISSN: 2220-6655 (Print); 2222-5234 (Online)
Website: https://www.innspub.net
Email contact: info@innspub.net
Vol. 27, Issue: 5, p. 40-72, 2025

INNSPUB

REVIEW PAPER

OPEN ACCESS

Unravelling the complex interactions between microplastics and PPCPs: The environment and health implications

Roshy Ann Mathews[1], S. Rajakumar[2], N. Aishwarya[2], M. Prashanthi Devi*[1]

[1]*Department of Environmental Science and Management, Bharathidasan University, Tiruchirappalli, Tamil Nadu, India*

[2]*Department of Marine Biotechnology, Bharathidasan University, Tiruchirappalli, Tamil Nadu, India*

Key words: Microplastics-PPCPs interaction, Bioavailability, Desorption, Toxicological synergy, Biofilm formation

DOI: https://dx.doi.org/10.12692/ijb/27.5.40-72 Published: November 08, 2025

ABSTRACT

The microplastics and pharmaceuticals and personal care products (PPCPs) interaction is a serious environmental problem that has higher impactson both the ecosystems and human health. The presence of microplastics within various environments and the widespread use of PPCPs, leads to complex that make the toxic compounds more persistent and bioavailable. The large surface area, hydrophobicity, and chemical additives of the microplastics, make them effectively adsorb PPCPs. The PPCPs bioaccumulate in aquatic species as a result, which suppresses the contaminants' natural breakdown processes. Bioaccumulation can increase the possibility of biomagnification through food webs, which increases the concerns about chronic toxicity. These microplastic-PPCP complexes facilitate wide transportation across aquatic, terrestrial, and atmospheric pathways and therefore contaminate the ecosystems. Persistent pollutants cause harm to biodiversity, disrupt necessary ecosystem services, and affect health through contaminated food and water supplies. Thus, studies have evidenced that microplastics ingested by marine biota result in the desorption of adsorbed PPCPs under diverse environmental conditions and also increase exposure level to harmful products. Furthermore, the use of contaminated aquatic products and contaminated drinking water are likely to also affect human beings, such impacts include: importing ARGs within the gut, which might imply the antibiotic resistance. This study reviews the interaction and the mechanisms that cause long term complexity of microplastic-PPCPs in the environment, emphasizing the necessity to reduce their impact on ecosystems and public health through advanced solutions and policies. Advances in multidisciplinary research and waste management practices are needed to conserve ecosystems and bring in a sustainable future.

***Corresponding author:** M. Prashanthi Devi ✉ prashanthidevi@gmail.com
* https://orcid.org/0000-0002-5500-6085

First author: Roshy Ann Mathews: https://orcid.org/0000-0003-4718-4014

Co-authors:

S. Rajakumar: https://orcid.org/0000-0001-5122-4491

N. Aishwarya: https://orcid.org/0000-0003-2463-0624

INTRODUCTION

Microplastics (MPs) are plastic particles under 5mm in size. They have emerged as persistent pollutants in the environment, capable of interacting with a wide range of contaminants, including heavy metals and PPCPs. These interactions can alter the chemical fate of PPCPs by increasing their persistence and bioavailability in aquatic and terrestrial environments.

According to recent studies, microplastics serve as vectors for the transmission of PPCPs, which causes risks to human health and the environment (Zhang *et al.,* 2023*;* Tumwesigye *et al.,* 2023).

Knowledge gaps and study objectives

Despite extensive study on microplastic contamination, little is known about the nature of interactions between microplastics and PPCPs. While some studies reveal synergistic effects, others demonstrate limited or varying results. In particular, the mechanisms of adsorption and desorption in diverse environmental conditions require more investigation. Moreover, it is unclear how the shape of microplastics such as fibres vs fragments affects the retention and transit of PPCPs. Microplastic-PPCP complexes' potential in stimulating antimicrobial resistance (AMR) is another emerging concern that requires further research.

The objectives of this study are examining the processes underlying PPCP adsorption on microplastics, evaluate environmental variables that affect their mobility and bioavailability, examine possible toxicity routes, including AMR hazards, and provide mitigating techniques and policy suggestions.

Microplastics as carriers for PPCPs

Microplastics can adsorb PPCPs from surrounding environments, especially in aquatic systems. This is due to their large surface area, hydrophobic properties, and the presence of functional groups that interact with chemical contaminants.

Microplastics have been found to adsorb a wide range of PPCPs, with the extent of sorption determined by both the compound's physicochemical features (e.g., hydrophobicity, charge, functional groups) and the polymer type. Table 1 summarises some instances of PPCPs that have been experimentally shown to bind to various types of microplastics. These interactions indicate how, in a variety of environmental conditions, microplastics may behave as carriers of antibiotics, endocrine disruptors, antimicrobials, and other therapeutic substances.

Mechanisms of adsorption: PPCPs such as antibiotics, hormones, and synthetic fragrances bind to microplastics through van der Waals forces, hydrogen bonding, and electrostatic interactions. Fig. 1 shows the different types interface interactions between the pharmaceutical compounds and microplastic surfaces.

Surface properties of microplastics

High surface area

Microplastics, especially those with irregular shapes or porous surfaces, provide a large area for PPCP adsorption. The increased surface area of these adsorbents allows greater interactions with the pollutant molecules leading to improved adsorption processes (Isaeva *et al.,* 2021; Honarmandrad *et al.*, 2023). Certain microplastics which have irregular shapes have been shown to have better adsorption due to their geometric forms. In comparison microbeads which have smooth and round surfaces are not too effective in adsorption whereas microplastics with a lot of irregularities on their surface are capable of capturing pollutants easily (Honarmandrad *et al.,* 2023). This increase in the complexity of the particles also increases the surface area that is available for adsorption, thus, increasing chances of adsorption with active interactions such as van der Waals and hydrogen bonding, which are fundamental to the adsorption phenomena (Liu *et al.,* 2017).

Various types of microplastics such as nurdles, fibers, microbeads, and fragments exhibit different adsorption capacities based on their shapes and sizes, influencing their effectiveness as adsorbents for contaminants in aquatic environments *(*Sulaiman *et al.,* 2023; Talukdar *et al.,* 2024).

Table 1. Examples of PPCPs adsorbed on microplastics

Type of compound	PPCP compound adsorbed	Microplastic type	Reference
Antibiotics	Ciprofloxacin	Polyethylene (PE)	Atugoda *et al.,* 2020
	Sulfamethoxazole	Polystyrene (PS)	Lu *et al.,* 2022
Endocrine disruptors	17α-ethinylestradiol	Polypropylene (PP), Polyethylene (PE), Polystyrene (PS).	Leng *et al.,* 2023
	Bisphenol A	Polyvinyl Chloride (PVC)	Chen *et al.,* 2024
Antimicrobials	Triclosan	Polyethylene	Castaño-Ortiz *et al.,* 2024
Anti-inflammatory drug	Diclofenac	Polystyrene (PS)	Li *et al.* 2022
Antidepressants	Fluoxetine	Polyamide (PA)	Arienzoand Donadio, 2023
Antiepileptics	Carbamazepine	Polyethylene Terephthalate (PET)	Zhang *et al.,* 2023

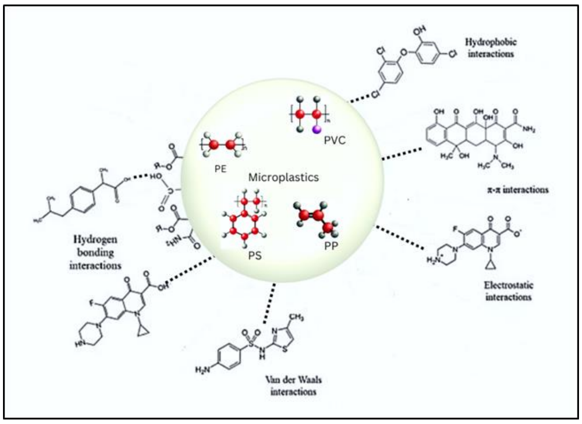

Fig. 1. Various interface interactions between the pharmaceutical compounds and microplastic surfaces

The surface structure of microplastics also governs biofouling. These processes result in the accumulation of microorganisms on the surface of microplastics. The presence of irregular shapes in the particles usually promotes the growth of biofilm which promotes the retention of pollutants through biological means. For instance, it has been noted that films and fragments are seen to favor higher biofilm growth than spherical microplastics, thereby increasing their overall pollutant adsorption capacity (Rai *et al.*, 2022; Rozman *et al.*, 2023).

Hydrophobicity

Many microplastics, such as polyethylene and polypropylene, are hydrophobic, making them ideal for binding non-polar PPCPs due to their affinity (Bhagwat *et al.*, 2024). In aquatic environments, the hydrophilic nature of substances may attract water molecules and counteract adsorption by non-polar compounds. Hydrophobic microplastics minimize this competition, allowing for PPCPs to bind more efficiently. Once adsorbed onto hydrophobic surfaces, non-polar PPCPs are retained more effectively due to the stabilizing hydrophobic interactions (Zheng *et al.,* 2024). This retention may lead to longer exposure time of aquatic organisms to these pollutants, which raises concerns about bioaccumulation and toxicity.

Electrostatic interactions

Electrostatic interactions occur when charged PPCPs interact with the functional groups present on the surfaces of microplastics. The positively or negatively charged PPCPs, such as ionic medications, adsorb on microplastics with oppositely charged functional groups. These interactions are heavily influenced by surface properties of MPs, including their zeta potential and pH-dependent charge distribution. According to study, functionalized surface microplastics, such as those with hydroxyl or carboxyl functional groups, exhibit stronger electrostatic attraction to polar PPCPs (Hashem *et al.,* 2024).

π-π interactions

Adsorption of PPCPs on microplastic surfaces involves π-π interactions and hydrogen bonding. Aromatic PPCPs (such as antibiotics and hormone disrupting chemicals) can interact with the aromatic rings in microplastics through π-π stacking (Liu *et al.,* 2024).

Hydrogen bonding is observed, mainly inPPCPs with oxygen and nitrogen molecules which allowsits binding to the polar surface groups of microplastics. These interactions enhance the environmental persistence of PPCPs.

Van der Waals forces

Van der Waals force plays an important role in the weak molecular attraction between microplastics and PPCPs. These non-covalent interactions have a short range and alter the initial adherence of PPCPs to microplastics. Although van der Waals forces are less than hydrophobic and electrostatic interactions, they still retainthe PPCPs to the rough surfaced-microplastics.

Covalent bonding

Covalent bonding is another possible mechanism of interaction when microplastics have chemically reactive functional groups (such as amine, carboxyl and hydroxyl), they can form persistent covalent bonds with reactive PPCPs (Arienzoand Donaldo, 2023).

Surface entrapment and pore diffusion

The porous-structured microplastics such as microbeads or polystyrene can retain PPCPs on the surfaces. Micro-scale and nano-scale pores in microplastics allow small sized PPCPs to get entrapped in the polymer matrix (Matei *et al.*, 2022). This mechanism slows PPCP release and is most likely responsible for their long-term persistent in the environment.

Chemical additives

Additives in plastics, like plasticizers, can enhance the affinity for certain PPCPs, altering adsorption dynamics. Additives may add new functional groups or modify existing ones on the microplastic surface, which can facilitate various kinds of interactions with PPCPs (Han *et al.*, 2021). Chemical additives, such as plasticizers, modify the surface properties of microplastics. This thereby increases the hydrophobicity of the microplastic surfaces which further enhances their potential to adsorb non-polar PPCPs. For instance, the existence of plasticizers has been demonstrated to enhance lipophilicity in microplastics which facilitates more effective binding with hydrophobic contaminants (Hai *et al.*, 2020; Joo *et al.*, 2021).

Factors influencing microplastic-PPCP interactions

PPCP Characteristics

The characteristics of pharmaceuticals and personal care products (PPCPs) play a significant role in influencing their interactions with microplastics.

Chemical structure

Hydrophobic PPCPs, such as triclosan (log Kow ≈ 4.8), have higher adsorption to microplastic surfaces than hydrophilic compounds. Cortés-Arriagada *et al.* (2023) and Yu *et al.* (2024) observed triclosan distribution coefficients (Kd) ranging from 10^3 to 10^4 L/kg, indicating strong physisorption. On the other hand, more hydrophilic substances like carbamazepine (log Kow ≈ 2.5) and sulfamethoxazole (log Kow ≈ 0.9) typically exhibit significantly lower adsorption (Kd < 10^2 L/kg) (Das *et al.*, 2017). Microplastic ageing improves triclosan uptake by increasing surface roughness and oxygen-containing functional groups, resulting in increased sorption efficiency.

The structural properties of microplastics, including their crystallinity and surface morphology, significantly influence their adsorption capacities. For instance, different types of microplastics, such as polyethylene (PE), polypropylene (PP), promote the diffusion and sorption of hydrophobic PPCPs like triclosan. Higher crystallinity polymers, such as PLA and polylactic acid, on the other hand, typically have more tight molecular packing, which can limit adsorption by reducing sorption sites. Similarly, hydrophilic surfaces may preferentially interact with ionisable or polar PPCPs by hydrogen bonding or electrostatic forces, while hydrophobic polymers (PE, PP) adsorb hydrophobic PPCPs more effectively than hydrophilic polymers. For example, Zhang *et al.* (2024) highlighted the combined effects of surface and crystallinity by reporting triclosan adsorption coefficients that were roughly 2-3 times greater on PE and PP than on PLA.

Polarity and charge

Polar PPCPs, like antibiotics, may interact with microplastics via ionic bonding, depending on environmental conditions. Some polar PPCPs are also influenced by pH or salinity.

Research indicates that the adsorption capacity of antibiotics on microplastics varies significantly as environmental conditions change. For example, the environment influences the ionic forms in which tetracycline (TC) occurs with varying pH levels. Depending on the pH level, TC can become positively charged and thus readily interacts with negatively charged microplastic surfaces (Li *et al.*, 2018; Zhou *et al.*, 2024).

Environmental factors

Environmental factors such as pH, salinity, and temperature also regulate the interactions between PPCPs and microplastics, significantly influencing adsorption dynamics, mobility, and bioavailability of PPCPs in aquatic environments.

pH

Adsorption efficiency varies with pH, which can influence the charge of PPCPs and the surface chemistry of microplastics. Many PPCPs have pH-dependent ionization states.

Studies show that the adsorption of several harmful chemicals, such as sulfamethoxazole and diclofenac, depends significantly on pH, in which increasing the pH tends to improve the adsorption of some organic pollutants by microplastics but deter others at different ionic forms (Zhao *et al.*, 2022; Liang *et al.*, 2023).

Concentration rate in freshwater and marine

The concentration of microplastics is often more pronounced in freshwater ecosystems than in marine environments, influenced by various inherent properties of microplastics and environmental factors. Inherent properties ofmicroplastics, such as size, shape, and density, play a crucial role in their movement (Arienzo *et al.*, 2023; Pan *et al.*, 2023). High-density microplastics have a greater tendency to settle and accumulate in sediments of freshwater and marine ecosystems. This process can cause sedimentation, and hence, result in localized microplastic pollution hotspots in benthic environments, where they might interact with organisms dwelling on the sediment (Darabi *et al.*, 2021). Lightweight microplastics such as polyethylene and polypropylene float on the surface of water bodies, whereas heavier materials such as polystyrene and polyvinyl chloride settle at the bottom of water bodies (Gani *et al.*, 2024).

Salinity and temperature

Higher salinity in marine environments can enhance adsorption by reducing PPCP solubility in water. A study reported that salinity increase enhanced the adsorption efficiency of tetracycline on PVC microplastics by enhancing interactions through ionic bonding mechanisms (Liang *et al.*, 2023). However, salt concentrations may also influence electrostatic interactions between charged PPCPs and microplastic surfaces. Precisely, divalent cations such as Ca^{2+} and Mg^{2+} may promote adsorption through the bridging between negatively charged sites on microplastics with anionic forms of PPCPs (Joo, 2021).

Temperature variations can influence the solubility of PPCPs and their strength of interaction with microplastics. Some studies have reported that under water warming, the solubility of tetracycline and some other antibiotics such as amoxicillin, diclofenac increases at the same time as they increase desorption from microplastic surfaces through certain conditions (Mei *et al.*, 2020; Liang *et al.*, 2023).

Impacts of microplastic-PPCP complexes

Enhanced persistence

PPCPs adsorbed onto microplastics are shielded from degradation processes such as photolysis and microbial activity. These contaminants tend to persist in the environment for long stretches of time by acting as a reservoir in microplastics. A study reported that there was a significant lower degradation rate of tetracycline adsorbed onto PVC microplastics compared to tetracycline molecules present in the aqueous phase. This is due to the formation of a protective barrier around the antibiotic which limits exposure to degrading agents in the environment. This protective effect may lead to prolonged persistence of tetracycline in aquatic systems with unknown ecological impacts (Zahmatkesh *et al.*, 2023).

Bioavailability and desorption-ingestion by organisms

Aquatic organisms can ingest microplastic-PPCP complexes, leading to internal desorption in acidic or enzymatic environments, increasing toxicity. Studies have shown that when fish ingest microplastics adsorbed with antibiotics such as tetracycline, the acidic conditions of the stomach result in the desorption of such contaminants (Wang *et al.*, 2024). This increases the organism's bioavailability of the desorbed antibiotics, which increases the possibility of antibiotic resistance as well as their harmful effects (Dick *et al.*, 2024).

Environmental desorption

Changes in pH, salinity, or temperature can release PPCPs back into the water, creating localized pollution hotspots. This desorption may significantly impact water quality and ecosystem health. A study noted that the pH variations may enhance the desorption of tetracycline from PVC microplastics into the water again. The experiment found that at lower pH, the microplastics exhibited reduced adsorption capacity because of electrostatic repulsion between the negatively charged microplastics and the anionic forms of tetracycline. This implies that fluctuations in environmental pH might play a very crucial role in the mobility of tetracycline in aquatic ecosystems (Liang *et al.*, 2023; Stapleton *et al.*, 2023).

Toxicological synergy

Microplastics carrying PPCPs can amplify toxic effects in organisms, combining physical blockages caused by plastics with chemical toxicity from PPCPs. This synergistic effect can cause a multiplicative health impact on aquatic organisms. Recent studies demonstrated that microplastics with adsorbed antibiotics not only caused physical injury through physical blocking of digestive tracts but also contributed to chemical toxicity that can reduce growth and reproduction in aquatic organisms. The interactions were even demonstrated to be more detrimental than exposure to either stressor alone (Han *et al.*, 2021; Du *et al.*, 2024).

Transport and bioavailability of microplastics and PPCPs

When microplastics adsorb PPCPs, they serve as vectors, transporting these contaminants across different environments. The transport and bioavailability of microplastics and PPCPs are interconnected processes that have significant implications for ecosystem health and biodiversity. For instance, it has been found that polystyrene microplastics can adsorb pharmaceuticals including sulfamethoxazole and transport them across freshwater systems, altering their bioavailability (Sun *et al.*, 2024). Their persistent and pervasive nature necessitates integrated approaches to mitigation, focusing on reducing sources, improving wastewater treatment, and providing bio-alternatives to plastics.

The environmental transport and bioavailability of microplastics and pharmaceuticals and personal care products (PPCPs) are critical to understanding their ecological and health impacts. These pollutants are widely distributed across terrestrial, freshwater, and marine ecosystems due to their persistence, mobility, and interactions with environmental factors.

Microplastics facilitate the movement of PPCPs across ecosystems

Long-range transport and enhanced mobility

Microplastics containing PPCPs can travel long distances via ocean currents or atmospheric pathways, depositing contaminants in previously unaffected regions and distributing pollutants to remote ecosystems. To increase ciprofloxacin's persistence and bioavailability, Atugoda *et al.* (2020) showed that polyethylene microplastics might adsorb the antibiotic and make it easier for it to move through freshwater systems. According to Li *et al.* (2022), polystyrene microplastics exhibited strong affinity and mobility potential as they absorbed sulfamethoxazole with partition coefficients as high as 10^4 L/kg. These results demonstrate that hydrophobic organic pollutants, such as PPCPs, can be efficiently transported by microplastics throughout aquatic ecosystems, increasing their ecological risk and long-range diffusion.

Increased bioavailability

The sorbed PPCPs can desorb in specific conditions, releasing concentrated contaminants into organisms or environments. For example, acidic or enzymatic conditions in the digestive tracts of marine organisms can release PPCPs from ingested microplastics. A study on freshwater ecosystems highlighted the potential risks of microplastics from plankton to fish.

It highlighted the ability of microplastics to transport PPCPs in food webs, causing them to get biomagnified from the planktons to larger predators feeding on the fish, their associated ecological risks and health effects on fish (Gao *et al.*, 2025).

A study showed that both polystyrene and polyethylene could adsorb PPCP contaminants, such as 17α-ethinylestradiol, chlorpyrifos, and benzo(α)pyrene from the water surrounding them. Once ingested in the fish, these microplastics help to transfer contaminants to the organisms, thus indicating that microplastics can be vectors for hazardous chemicals in aquatic ecosystems (Ašmonaitė *et al.*, 2020). For instance, the tenfold enhancement of biomagnification was determined for fish that were exposed to venlafaxine along with PVC microplastics when compared to the fish that received only venlafaxine. Such bioavailability enhancements via microplastics might make accumulation of these particular pharmaceuticals into aquatic organisms a reality (Ribeiro *et al.*, 2023).

Transport mechanisms

Microplastics and PPCPs are transported through a variety of pathways, influenced by their physical and chemical properties as well as environmental conditions.

Aquatic systems

Surface water

Microplastics, due to their low density (e.g., polyethylene, polypropylene), often float and travel long distances via rivers and ocean currents. PPCPs that are dissolved in water or adsorbed onto microplastics can follow these currents, dispersing to remote areas.A study done in Kattegat/Skagerrak region in Denmark found out the existence of microplastics throughout a water column, from the upper surface to bottom depth and their concentrations varied at different depths. High density polymers of high density occurred with a proportionally high magnitude which could influence their vertical displacement. This gradient means that fish in various regions may be exposed to different concentrations of microplastics depending on their depth and density (Lenaker *et al.*, 2019; Gunaalan *et al.*, 2024). The various sources of microplastics and PPCPs and the route of entry of these contaminants in the environment is shown in Fig. 2.

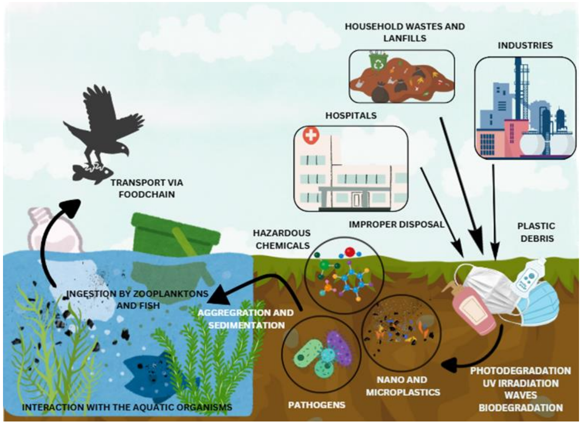

Fig. 2. Transport of PPCPs and microplastics in terrestrial and aquatic environments

Sedimentation

Heavier microplastic-PPCP complexes may settle in sediments, creating reservoirs of pollutants that can re-enter the environment under changing conditions. Denser microplastics (e.g., polyvinyl chloride) or those aggregated with biofilms and sediments can sink, depositing in riverbeds, lakes, and ocean floors. PPCPs sorbed onto microplastics or particles in sediments may persist as localized pollution hotspots. It is evident that microplastics of higher densities tend to settle in benthic environments where they can interact with sediments and aquatic organisms. For example, a study noted that microplastics are retained in seagrass canopies, acting as sinks for these pollutants due to their negative buoyancy and aggregation with organic matter. This retention leads to increased exposure for benthic organisms and alters local ecological dynamics (Radford *et al.*, 2024; Patterson, 2025).

A study done by Joo *et al.* (2021) shows that enriched sediments with microplastics changed the structure and function of sedimentary microbial communities, affecting processes of nitrogen cycling. It has been shown that different microplastics like polyethylene (PE), polyvinyl chloride (PVC), and polyurethane foam (PUF) differently affect nitrification and denitrification rates, and therefore, show that the type of microplastic could influence both PPCPs retention or release (Anthony *et al.*, 2024).

Atmospheric transport

Microplastics, especially smaller particles, can become airborne and travel significant distances through wind. PPCPs may volatilize into the atmosphere (e.g., fragrances) or adhere to airborne microplastics, contributing to their dispersion. This transport mechanism through the atmosphere raises concerns regarding their reaching and, consequently, their effects in the more remote areas away from the source ecosystems. PA6 possessed high adsorption capacities towards the hydrophilic PPCPs, namely Sulfacetamide, Chloramphenicol, Benzophenone-2 (BP-2), through different adsorption mechanisms modulated by pH and ionic strength (Sun *et al.*, 2024). Research found that airborne microplastics can be transported over long distances, affecting remote regions like Antarctica (Chen *et al.*, 2023).

Soil and groundwater

Soil contamination

Agricultural application of biosolids and irrigation with contaminated water introduces microplastics and PPCPs into soils. Biosolids, nutrient-rich by-products of wastewater treatment, are applied to agricultural lands to improve fertility. These biosolids may contain residual PPCPs that were not fully degraded during wastewater treatment. Studies have shown that microplastics can alter soil physicochemical properties, disrupt nutrient cycling, and affect microbial communities, which are essential for maintaining soil fertility. For instance, a recent study revealed that the rate of fertilizer application would exponentially increase the concentration of microplastics in agricultural soils, which will reach levels over a century that will significantly affect the soil health (Sheikh *et al.*, 2025). Additionally, the presence of PPCPs in these soils may have adverse effects on soil organisms and may also pose risks to human health through the food chain (Liu *et al.*, 2025).

Leaching to groundwater

PPCPs that are highly soluble in water can seep into groundwater, especially in sandy or broken soils, when combined with mobile microplastics that move within soil pores. For instance, it has been demonstrated that the chemotherapy medication fluorouracil, which is frequently used to treat cancer, can adsorb onto polypropylene (PP) microplastics; the adsorption capacity of PP was lower than that of polyvinyl chloride (PVC) and polyamide 6 (PA6) (Sun *et al.*, 2024). With a half-life of roughly 20 to 50 days in soil, fluorouracil demonstrates environmental persistence despite this reduced adsorption, providing ample time for leaching (Dick *et al.*, 2024). Furthermore, field research shows that in high-permeability soil conditions, PPCPs carried by microplastics can enter subterranean layers and make their way to groundwater in a matter of weeks to months (Prata *et al.*, 2020).

Persistence in soils raises the potential of groundwater pollution, and crops irrigated with contaminated groundwater may absorb PPCPs, which could lead to bioaccumulation and food-chain transfer issues (Boxall, 2012). These risks are significant. This emphasises how critical it is to track PPCP–microplastic complexes in agricultural soils that have had biosolids amended and to create mitigation plans to reduce the amount of groundwater exposure pathways.

Factors influencing transport

Environmental conditions

pH and salinity

In aquatic systems, pH and salinity control the movement and aggregation of microplastics in addition to affecting the sorption of PPCPs. According to Zahmatkesh *et al.* (2023), tetracycline adsorption onto polyethylene microplastics, for instance, was found to peak at alkaline circumstances (pH = 10), with adsorption efficiency dropping by about 40% at near-neutral pH. The function of ionisation states in PPCP–plastic interactions was further demonstrated by fluoxetine's enhanced sorption in acidic environments (pH 5–6) (Li *et al.*, 2021).

Salinity has a significant impact as well. In estuarine conditions, the electrically charged double layer of microplastic particles can be compressed by Na+ and Cl+ ions, which encourages the aggregation and co-sorption of hydrophobic substances. For example, compared to freshwater conditions, the adsorption of bisphenol A on polystyrene microplastics increased by approximately 25% at salinities higher than 30‰ (Zhang *et al.*, 2022). This implies that the long-distance movement of PPCP–microplastic complexes from freshwater to marine environments may be facilitated by salinity-driven aggregation.

Temperature

Increased temperature can increase the kinetic energy of molecules, which can, in turn, improve the rates of desorption of PPCPs from microplastics. Moreover, higher temperatures can cause faster degradation of some types of microplastics, which can influence their surface properties and, subsequently, their adsorption properties (Dick *et al.*, 2024).

Chemical properties

Hydrophobic PPCPs (e.g., triclosan) tend to adsorb onto microplastics, enhancing their co-transport. This increased adsorption is due to the fact that hydrophobic interactions enable these compounds to be more attracted to non-polar surfaces of microplastics (Dick *et al.*, 2024).

Hydrophilic PPCPs remain dissolved, often moving with water flow. The adsorption capacities of sulfacetamide and chloramphenicol onto microplastics were lower than those of their hydrophobic counterparts, and pH and ionic strength have significant effects on the adsorption behaviour of these hydrophilic compounds (Sun *et al.*, 2024).

Particle size

Smaller microplastics (e.g., nanoplastics) have greater mobility in water and air, facilitating long-distance transport.Research indicates that nanoplastics can remain suspended in the water column due to their low density, allowing them to be transported over vast distances in aquatic environments. Additionally, the unique physicochemical properties of nanoplastics contribute to their stability and mobility; they can aggregate with other particles, altering their behavior and distribution in the environment (Ducoli *et al.*, 2025; Gigault and Davranche, 2025).

Bioavailability

The bioavailability of microplastics and PPCPs refers to their potential to interact with and be taken up by organisms. This concept is essential for understanding the ecological risks associated with plastic pollution and chemical contamination in aquatic and terrestrial environments.

Bioavailability of microplastics

Ingestion

Aquatic organisms mistake microplastics for food due to their size and appearance, leading to ingestion. Filter-feeding animals like salps, bivalves, and several fish species ingest microplastics. Thus, it might lead to physiological effects. Microplastic particles were detected in 100% of water samples collected in the Tropical Eastern Pacific and also in the digestive tracts of some marine animals like fish and squid (Alfaro-Núñez *et al.*, 2021).

In terrestrial systems, microplastics can enter food chains through soil-dwelling organisms. deep-burrowing earthworm Lumbricus terrestris enhances vertical transport of nanoplastics in soil. The study revealed that ingestion and subsequent excretion by earthworms led to substantial vertical transport of palladium-doped polystyrene nanoplastics with 256 nm in diameter (Heinze *et al.*, 2021).

Translocation

Microplastics can translocate across biological barriers, such as the gut epithelium, entering tissues and potentially affecting physiological functions. The jellyfish *Aurelia* sp. has been found to ingest microplastics by adhesion to their oral arms, showing the ways in which, these particles can enter food webs via filter-feeding organisms (Costa *et al.*, 2021). In similar manner, advanced in vitro models have shown that microplastics can translocate through lung and gut epithelial barriers. For instance, polystyrene particles with diameters of 0.05 μm to 10 μm have been found to cross epithelial cells in lung and intestinal models, suggesting that they could reach systemic circulation (Donkers *et al.*, 2022).

Bioavailability of PPCPs

Bioavailability of PPCPs is a critical issue in environmental science as it deals with the way PPCPs interact with and are absorbed by living organisms.

Direct exposure

Aquatic organisms absorb PPCPs directly from contaminated water. A seminal study by Kolpin *et al.* (2002) reported that more than 80% of the streams sampled throughout the United States contained at least one type of PPCP, with many detected at concentrations in the parts per trillion (ppt) range. This widespread contamination indicates that aquatic organisms are frequently exposed to these substances. Recent studies revealed that certain PPCPs were able to induce transgenerational effects in aquatic organisms, affecting reproductive competency and behavioral traits across generations (Marcu *et al.*, 2023; Pinto and Aneck, 2025).

Terrestrial organisms may be exposed through ingestion of contaminated food or water. Biosolids use in agriculture has been proven to lead to the introduction of PPCPs into the soil environment, some PPCPs like carbamazepine, atenolol paracetamol and ibuprofen have a very long persistence time in the soil and may be accumulated by plants (Pérez-Lucas *et al.*, 2024). Kibuye *et al.* (2019) found several pharmaceuticals in the groundwater wells that supply drinking water, thus there is a risk to the terrestrial biota and humans through groundwater contamination.

Microplastic-PPCP desorption

Microplastics could significantly affect the bioavailability of pharmaceuticals and personal care products in aquatic environments. PPCPs sorbed to microplastics may concentrate these chemicals at ingestion sites, as well as provide a potential for desorption within the digestive systems of organisms.

PPCPs sorbed onto microplastics may enhance their bioavailability by concentrating these chemicals at ingestion sites. A recent study by Zahmatkesh Anbarani (2023) has examined the adsorption behavior of tylosin, chloramphenicol and tetracycline onto common environmental microplastics such as PE, PS, and PVC. The results indicate that PVC has the highest adsorption capacity for both antibiotics, due to its functional groups and crystallinity, therefore the aquatic organisms exposed to these particles with adsorbed antibiotics exhibit physiological changes, including alterations in feeding behavior.

Once ingested, PPCPs may desorb in the acidic or enzymatic environment of an organism's digestive system. This desorption process may liberate the adsorbed PPCPs in the organism tissues, which might result in toxicological effects. It has been proven that ibuprofen can be adsorbed onto microplastics, which considerably influences its bioavailability. The acidic conditions in the stomach may enhance the desorption of ibuprofen from microplastics upon ingestion by fish, increasing the concentrations of the drug in the bloodstream (Arienzo *et al.*, 2023). These are processes that exhibit the effects of xenobiotics as foreign materials which interrupt normal biological activities. These cause disruptions in the normal endocrine pathways and metabolism within aquatic animals that could pose a risk to particular species as well as food chains (Zhu *et al.*, 2023).

Combined effects of microplastics and PPCPs

The co-transport of microplastics and PPCPs amplifies their environmental impact:

Chemical loading: Microplastics act as carriers, increasing the amount of PPCPs available in ecosystems. Due to the higher surface area, microplastics are able to adsorb numerous toxic substances such as PPCPs, and the amount of these chemicals increases.

Thus, due to adsorption ability, microplastics can serve as a vector, enabling the movement of PPCPs across diverse environments (Yu *et al.*, 2022; Yarahmadi *et al.*, 2024).

Localized hotspots: Sediments and biofilms on microplastics can concentrate PPCPs, creating zones of high toxicity. These concentrations may produce zones that have significantly higher toxicity due to the PPCPs accumulating (Castaño-Ortiz *et al.*, 2024). Such hotspots are especially alarming in marine systems where floating microplastics can adsorb hydrophobic PPCPs, such as bisphenol A, causing their deposition at distant shorelines (Gani *et al.*, 2024).

Trophic transfer: Both microplastics and PPCPs can bioaccumulate and biomagnify in food chains, affecting top predators, including humans (Arienzo *et al.*, 2023; Nguyen *et al.*, 2023). As smaller organisms ingest microplastics, they also take up the associated PPCPs, which can then be transferred to larger predators, including humans. This process raises concern about the potential health impacts on top predators due to the accumulation of these harmful substances (Hashem *et al.*, 2024).

Transport and bioavailability in ecosystems

Microplastics, due to their pervasive presence in various ecosystems, they have become great vectors to transport pharmaceutical and personal care products (PPCPs). This facilitates the enhancement of bioavailability of the contaminants, as it relates to being hazardous to environment and human. Table 2 shows the examples on transport and enhanced bioavailability of microplastics and PPCPs into different ecosystems.

Toxicity amplification of microplastics and PPCPs

The co-occurrence of microplastics and pharmaceuticals and personal care products (PPCPs) in the environment leads to toxicity amplification, a phenomenon where their combined presence intensifies harmful effects on ecosystems and organisms. This interaction creates synergistic impacts that are more severe than those caused by either pollutant alone.

The synergistic interactions between microplastics and PPCPs significantly amplify their toxicity, posing a serious threat to ecosystems and human health. Addressing this issue requires interdisciplinary efforts to mitigate sources, advance treatment technologies, and promote sustainable practices to reduce their environmental footprint.

The combination of microplastics and PPCPs can lead to synergistic toxic effects on organisms, impacting their health and the environment.

Combined stressors

Microplastics can cause direct damage to organisms, such as clogging digestive systems, and the leaching of PPCPs introduces a chemical level of toxicity. Such a combination of exposures may disturb metabolic processes, reproduction, and behavior in aquatic life. For instance, it has been proven that the combination of different PPCPs with microplastics can cause synergistic toxicity even at concentrations below harmful levels for each individual.

This phenomenon raises concerns about the ecological impact of low-level exposures to multiple contaminants, which can disrupt metabolic processes and lead to adverse effects on non-target organisms (Yang *et al.*, 2024).

Table 2. Transport and bioavailability of microplastics and PPCPs in various ecosystems

Ecosystem type	Transport and bioavailability	Compounds involved	Reference
Marine	Floating microplastics adsorbed with hydrophobic PPCPs travel across oceans and wash ashore on distant coastlines.	Bisphenol A, Polycyclic Aromatic Hydrocarbons (PAHs)	Yarahmadi *et al.,* 2024
Freshwater	Rivers carry microplastics and dissolved PPCPs downstream, where they accumulate in deltas and estuaries.	Ibuprofen, Caffeine, Diclofenac	Gupta *et al.,* 2024
Groundwater	Groundwater contamination occurs through leaching from soils where microplastics and PPCPs have been introduced.	Ofloxacin, Caffeine	Picó *et al.,* 2020
Soils	Agricultural practices introduce antibiotics bound to microplastics into soils, affecting microbial communities.	Tetracycline, Sulfamethoxazole, Chloramphenicol	Wang *et al.,* 2021

Endocrine disruption

Microplastics can adsorb endocrine-disrupting PPCPs like bisphenol A or synthetic hormones. These substances may exacerbate hormonal imbalances in organisms. Research suggests that microplastics are vectors for these harmful substances, thus increasing their bioavailability and potential endocrine disruption. For instance, it has been established that microplastics can increase the bioaccumulation of bisphenol A in aquatic organisms, causing reproductive and developmental problems. The interaction of microplastics with endocrine disruptors is significant because such an interaction may impact the long-term ecological consequences as the result of hormonal imbalances in wildlife (Atugoda *et al.*, 2021; Zhang *et al.*, 2023).

Mechanisms of toxicity amplification

The interaction between microplastics and PPCPs results in an amplified toxicity through several mechanisms. Understanding these mechanisms is necessary for assessing the environmental and health impacts of these contaminants.

Microplastics as carriers of PPCPs

Microplastics have a large surface area and exhibit hydrophobic properties, making them effective adsorbents for PPCPs. This adsorption increases the persistence of PPCPs in the environment, prolongs exposure times, and enhances their bioavailability to organisms. For example, it has been shown that microplastics could adsorb a broad spectrum of PPCPs with different adsorption capacities depending on the type of microplastic and the chemical nature of the PPCPs involved. Long-term aged microplastics were found to have significantly higher adsorption capacities for PPCPs compared to fresh microplastics, suggesting that aging processes increase their capacity to retain contaminants. This increase in adsorption capacity can be attributed to changes in the surface area and structure of the microplastics during the aging process. A study showed that, the total adsorption capacity of long-term aged microplastics ranged from 7,114.0 to 13,114.4 μg/g, which is much higher than the 171.8 to 1,043.7 μg/g found in fresh microplastics. The aging process leads to the formation of additional surface functional groups and alterations in the microplastic structure, which create more active sites for adsorption (Yao *et al.*, 2023; Santana *et al.*, 2025).

Desorption in biological systems

When microplastics are ingested by organisms, they can lead to the release of adsorbed PPCPs in their digestive systems due to changes in environmental conditions such as pH, salinity, and enzymatic activity. Thus, localized release leads to higher concentrations of PPCPs at the point of interaction, which amplifies their toxic effects on tissues and cells.

According to research, microplastics can desorb contaminants once ingested and exposed to physiological conditions, leading to increased local concentrations of toxic substances. For instance, a study by Atugoda *et al.* (2021) explained that microplastics may desorb adsorbed hydrophobic organic pollutants from aquatic organisms, thus leading to high bioaccumulation and potential toxic effects.

Additive and synergistic effects

Microplastics can cause physical harm, such as inflammation and gut blockage, while PPCPs contribute chemical toxicity. Collectively, they add cumulative stress to organisms, breaking down their physiological defences and exacerbating toxic effects. The combination of physical stress by microplastics and chemical stress by PPCPs might lead to more severe ecological consequences than either contaminant alone. The presence of microplastics enhances the oxidative stress caused by PPCPs, which further leads to cellular damage in aquatic organisms. The review added that this interaction could impair immune responses and reproductive success in aquatic species (Zhou *et al.*, 2020; Subaramaniyam *et al.*, 2023; Hong, 2025).

Ecotoxicological impacts

The microplastics and pharmaceuticals and personal care products (PPCPs) complex in aquatic and terrestrial ecosystems poses significant ecotoxicological risks.

Aquatic ecosystems

Fish and invertebrates

Microplastics adsorbing PPCPs can disrupt feeding, growth, and reproduction in aquatic organisms. For instance, exposure to microplastics carrying endocrine-disrupting chemicals like bisphenol A has been shown to lead to hormonal imbalances and reproductive failures in fish. A study by Reis (2022) found that fish exposed to microplastics containing bisphenol A exhibited altered reproductive behaviours, reduced fertility, and developmental abnormalities.

The presence of these contaminants can interfere with hormone signalling pathways, leading to significant ecological consequences.

Biofilm formation

Microplastics in water ecosystems generally form biofilms. These are communities of microbes attached to surfaces. They produce hotspots where PPCPs tend to accumulate, enhancing the toxicity of both the microplastics and the chemicals that get adsorbed.

According to Castaño-Ortiz *et al.* (2024), biofilms attached to microplastics, besides trapping PPCPs inside the particles, alsomodify physicochemical properties of microplastics, which makes them even more toxic. The formation of biofilms promotes horizontal gene transfer within bacteria that may result in the transmission of antibiotic-resistance genes in aquatic systems.

Terrestrial ecosystems

Soil microorganisms

In terrestrial ecosystems, antibiotics attached to microplastics can interfere with the microbial communities in soils. This reduces soil fertility and changes nutrient cycles. A study by Aralappanavar *et al.* (2024) showed that microplastics laden with antibiotics significantly affected the composition of soil microbial communities, thereby reducing microbial.

The existence of microplastics altered the composition of antibiotic resistance profiles during nitrification, indicating that these contaminants significantly affect microbial interactions and nutrient cycles (Liu *et al.*, 2025). Such interference can have cascading effects on plant health and soil productivity.

Earthworms and soil invertebrates

Ingestion of microplastic-PPCP complexes affects growth, reproduction, and behavior, disrupting their role in soil health.Research showed that microplastics along with PPCPs such as enrofloxacin and ciprofloxacin showed synergistic effect on the invertebrate species of Pseudomonas aeruginosa and Escherichia coli, which led to osmotic imbalance, cell membrane damage, obstructed the DNA replication and oxidative stress (Wu *et al.*, 2022; Du *et al.*, 2024). Exposure to microplastics loaded with PPCPs depressed earthworm reproduction and slowed the growth rates. Such impairment of growth and reproduction severely challenges their ecological functions, such as organic matter decomposition and nutrient cycling (Zhang *et al.*, 2024).

Human health implications

The interaction between microplastics and pharmaceuticals and personal care products (PPCPs) raises significant concerns regarding human health. As microplastics enter the food chain, they can carry harmful PPCPs, leading to various health implications.

Ingestion and bioaccumulation

Microplastics and PPCPs enter the human food chain through contaminated seafood, drinking water, and agricultural produce. Once inside the body, microplastics may act as vectors, releasing adsorbed PPCPs in tissues, potentially leading to localized toxicity.Microplastics deposits are observed in different human biological samples, such as blood, stool, and breast milk.

The ingestion of microplastics may lead to oxidative stress and inflammation, which may cause various health issues, including gastrointestinal disorders and chronic diseases. A study done in carp (*Cyprinus carpio*) revealed that this complex can easily pass through the blood-brain barrier resulting in significant biochemical changes including decreased activity of enzymes such as acetylcholinesterase and monoamine oxidase thereby resulting in impaired neural function (Hamed *et al.*, 2022; Yarahmadi *et al.*, 2024; Zheng *et al.*, 2024).

Combined toxic effects

Chemical toxicity

PPCPs such as antibiotics and hormones interfere with human hormonal and immune systems. A study showed that the combined presence of microplastic-PPCP such as polystyrene and roxithromycin can cause neurotoxicity, where microplastics were antagonistic, causing increased activity of superoxide dismutase (Arienzo *et al.*, 2023). PPCPs are known endocrine disruptors that may have adverse effects on growth, development, and reproductive health in humans (Dutta *et al.*, 2023). The presence of these compounds in the environment raises concerns about their long-term effects on human health.

Physical harm

Microplastics can cause inflammation and oxidative stress, exacerbated by the leaching of toxic PPCPs. Microplastic exposure has been associated with respiratory problems, cardiovascular diseases, and other inflammatory disorders. Physical damage from microplastics combined with chemical toxicity from adsorbed PPCPs has compounded the health risk for humans (Lee *et al.*, 2023). The microplastic particles tend to cause irritation and damage of epithelial cells, causing inflammation and even potential tissue injury. A study highlighted that the physical stimulation of these particles in the human body tends to trigger localized swelling and blockage in tissues due to their presence in the tissues. This form of physical irritation can exacerbate existing health issues and cause conditions like inflammatory bowel disease (IBD) (Kumar *et al.*, 2024; Li *et al.*, 2024).

Examples of toxicity amplification

Antibiotics and microplastics

Microplastics carrying antibiotics like sulfamethoxazole increase bacterial exposure to low doses of antibiotics, fostering the development of antibiotic-resistant bacteria, a phenomenon that poses a significant threat to public health.

Microplastics not only serve as carriers for antibiotics but also enhance horizontal gene transfer among bacteria, thereby facilitating the spread of antibiotic resistance genes (ARGs) in aquatic environments. The presence of biofilms on microplastics further increases the resistance levels of pathogenic bacteria since they provide a stable environment that fosters their growth and genetic exchange (Marathe *et al.*, 2022; Wang *et al.*, 2024). This is threatening since it can lead to treatment-resistant infections in humans, complicating standard medical practices and elevating healthcare costs.

Endocrine disruptors

Hormones like 17α-ethinylestradiol, when adsorbed onto microplastics, amplify disruptions in the reproductive systems of fish and amphibians.These endocrine-disrupting chemicals can leach into the tissues of organisms from microplastics, thereby affecting the levels of hormones in a manner that could interfere with reproduction and development. This issue a red flag in terms of potential similar effects in human reproductive health through the food chain via bioaccumulation. The microplastics with endocrine disruptors affected the reproductive behaviours and developmental processes of fish, which may be of relevance to human health if such mechanisms also occur in humans (Tang *et al.*, 2024; Zhao *et al.*, 2024).

Heavy metal adsorption

Microplastics carrying PPCPs can also adsorb heavy metals, creating multi-pollutant complexes with heightened toxicity.The bioavailability of toxic metals in human tissues increases when these complexes are formed, and this may be a cause for concern regarding the cumulative exposure risks. A study has shown that microplastics can enhance the uptake of heavy metals like lead and mercury in aquatic habitats. The bioaccumulation risk associated with this uptake is dangerous and harmful as these heavy metals contribute to neurotoxicity and other adverse health problems in humans. Moreover, the complex of heavy metals with PPCPs can enhance their toxicity and make it appear worse than what would be if either contaminant were present (Wang *et al.*, 2024; Zhao *et al.*, 2024).

Factors influencing toxicity amplification

Particle size

Smaller microplastics (nanoplastics) have greater surface area-to-volume ratios, increasing their capacity to adsorb PPCPs and penetrate biological barriers.The size of nanoplastics can more easily interact with the biological systems, and hence the adsorption of harmful substances increases. Smaller microplastics often tend to clump more in biological environments which, in return, can modulate their levels of bioavailability and toxicity profile. Once accumulated with biomolecules or other toxic contaminants, toxic compounds are leached out within a more bioactive form leading to an even higher level of damage to health (Bora *et al.*, 2024). According to a study conducted by Song *et al.* (2024), polystyrene microplastics may enter the bloodstream from the gastrointestinal tract and the respiratory system. Oxidative stress and inflammatory responses in myocardial cells indicate that the toxic effects are likely to be enhanced with smaller-sized particles.

Environmental conditions

The pH, salinityand temperature in the environment play a significant role in influencing the adsorption-desorption dynamics and bioavailability of PPCPs associated with microplastics.

They can influence the behavior of microplastics in the aquatic environments, hence their interaction with contaminants. For instance, changes in pH will alter the charge on the surface of the microplastics, impacting their ability to adsorb PPCPs (Bhuyan *et al.*, 2022). Besides this, temperature fluctuations may change the rates of microplastics' degradation, which further can lead to higher release of adsorbed chemicals into the environment.

Chemical properties of PPCPs

The chemical properties of PPCPs are essential for interaction with microplastics. Hydrophobic PPCPs, like triclosan and bisphenol A, have a greater tendency to associate with microplastics, thereby increasing persistence and bioaccumulation potential. It prolongs the exposure time of aquatic organisms and increases the possibility of toxic effects from persistent contaminants (Martín *et al.*, 2022).

Microplastics and PPCPs

Role in antimicrobial resistance (AMR)

The interplay between microplastics and pharmaceuticals and personal care products (PPCPs) plays a significant role in fostering antimicrobial resistance (AMR). This occurs through mechanisms such as biofilm formation, gene transfer among bacteria, and the prolonged persistence of antibiotics in the environment. Microplastics can act as hotspots for microbial colonization, creating a microenvironment for bacteria and other microorganisms.

Microplastics and PPCPs play a pivotal role in the emergence and spread of antimicrobial resistance by providing surfaces for microbial colonization, prolonging the environmental persistence of antibiotics, and facilitating gene transfer. Tackling this complex issue requires coordinated efforts to reduce pollutant sources, enhance waste management, and promote sustainable practices to curb the spread of AMR.

Biofilm formation

Microplastics provide biofilm support since they enable bacteria to cling and establish protective films against various physical and biological impacts. PPCPs, specifically antibiotic and antimicrobial species linked to microplastics, would seem to improve the establishment of such biofilms. Evidence already shows that microplastics support different microbial populations or communities including ARB.

The biofilm's physical structure is used to shield microbes from stress factors like antibiotics, leading to enhanced survival and subsequent possibilities of developing resistance (Zheng *et al.*, 2023).

Gene transfer

The proximity of resistant and non-resistant bacteria in these biofilms facilitates horizontal gene transfer, accelerating the spread of antimicrobial resistance.

Microplastics enhance gene exchange among microbial populations because bacteria in biofilms are closely spatially arranged. This can lead to rapid dissemination of Antibiotic resistant genes (ARGs), further complicating the management of antimicrobial resistance (AMR) (Jiao *et al.*, 2024).

Microplastics as hotspots for microbial activity

Microplastics have emerged as significant environmental pollutants that create favourable environments for microbial colonization, particularly in aquatic and soil ecosystems. This phenomenon promotes the spread of antimicrobial resistance (AMR) through various mechanisms.

Biofilm formation

Microplastics in aquatic and soil systems serve as surfaces for biofilm development, wherein bacteria aggregate and form protective layers. These biofilms often contain diverse microbial communities, including antibiotic-resistant bacteria (ARB). A study by Zheng *et al.* (2023) emphasize that microplastics support the growth of ARB within biofilms, which can lead to increased resistance levels in contaminated environments.The physical structure of biofilms protects microbes from external stresses, such as antibiotics, enhancing their survival and the potential for resistance.

Prolonged exposure to contaminants

Microplastics adsorb PPCPs, including antibiotics, creating localized high concentrations of these chemicals. For example, a research by Li *et al.* (2023) showed that microplastics like polyethylene (PE) and polystyrene (PS) adsorb antibiotics such as ciprofloxacin and sulfamethoxazole, which increases their transport and bioavailability in aquatic ecosystems.Prolonged exposure to sub-lethal antibiotic concentrations within biofilms induces selective pressure. This selective pressure can lead to the survival and proliferation of antibiotic-resistant bacteria (Tang, 2024).

PPCPs in selective pressure for AMR

PPCPs, particularly antibiotics, play a significant role in the development of antimicrobial resistance (AMR).

Environmental persistence of antibiotics

The persistence of the antibiotics ciprofloxacin and sulfamethoxazole is enhanced if they are adsorbed onto microplastics because they would last longer in the environment than when they occur alone. Such persistence is important as it enables the antibiotics to continue exerting selective pressure on microbial populations. Studies have found that microplastics enhance the half-life of the antibiotics in the aquatic environments, thereby making them available to bacteria.

A study by Li *et al.* (2022) demonstrated that microplastics could adsorb high concentrations of various antibiotics, thus prolonging the exposure period for microbial communities. The study further showed that the adsorption capacity of microplastics for these antibiotics increases not only their environmental persistence but also facilitates their accumulation in sediments and biofilms, where they exert selective pressure on bacteria. The prolonged exposure to sub-lethal concentrations of antibiotics within biofilms formed on microplastics induces selective pressure that favours the survival of antibiotic-resistant bacteria (ARB) (Ahmad *et al.*, 2024).

Non-antibiotic PPCPs and co-resistance

Non-antibiotic PPCPs (e.g., disinfectants, heavy metals, and endocrine-disrupting compounds) can also drive co-selection, where resistance to one compound confers resistance to others. This can occur through various mechanisms:

Cellular mechanisms: Exposure to non-antibiotic agents may result in physiological changes in bacteria that make them more resistant to a range of antimicrobial agents. Biocides used as disinfectants, for example, may select for resistance mechanisms that protect against antibiotics (Maillard *et al.*, 2024).

Genetic linkage: Resistance genes for non-antibiotic agents could be genetically linked to those for antibiotics. This means that when bacteria acquire resistance to one type of compound, they may also gain resistance to others due to the proximity of these genes on the same plasmid or chromosome (Partridge *et al.*, 2018).

Bacterial community structure: The presence of non-antibiotic PPCPs can change the structure of bacterial communities, making resistant strains dominant (Wu *et al.*, 2023). This results in increased interactions between resistant and susceptible bacteria, thereby promoting gene transfer.For example, exposure to triclosan (an antimicrobial in personal care products) has been linked to cross-resistance with antibiotics.

Horizontal gene transfer (HGT) on microplastics

Microplastics facilitate the transfer of antimicrobial resistance genes (ARGs) among bacteria through horizontal gene transfer:

Gene exchange in biofilms

Bacteria within biofilms on microplastics are in close proximity, enabling processes like conjugation, transduction, and transformation.Biofilms on microplastics may act as reservoirs for ARGs, allowing for quick spread even between distantly related bacterial species (Liu *et al.*, 2024).

ARGs in the environment

ARGs from resistant bacteria may adsorb onto microplastics, which then act as carriers, spreading resistance genes to new environments.When these microplastics are ingested by organisms, ARGs may enter the gut microbiome, further propagating resistance.

A study by Zheng *et al.* (2023) indicated that microplastics adsorb ARGs very effectively, especially in environments affected by wastewater discharge. The study underscored that the physical and chemical properties of microplastics make them an ideal substrate for microbial colonization and biofilm formation, where horizontal gene transfer (HGT) may occur.A study indicated that the aging of microplastics due to its increase in surface area improves its ability to capture and retain ARGs from the environment. Such a process promotes the transfer of resistance genes among bacteria in biofilms accumulated on these microplastics, mainly in the wastewater treatment plants as the conditions are favourable for gene exchange (Tang *et al.*, 2024).

Environmental pathways for AMR spread

The spread of antimicrobial resistance is a complex issue involving numerous environmental pathways, mainly through transport via microplastics and pharmaceuticals and personal care products. These routes contribute to the spreading of resistant bacteria and resistance genes through ecosystems, affecting public health to a great extent.

Aquatic pathways

Rivers and oceans become highways for microplastics carrying PPCPs and resistant bacteria, thus spreading AMR across regions. Transport of microplastics in aquatic environments is further facilitated by human activities, like discharge of sewage effluent and agricultural runoff, introducing antibiotic-laden microplastics into water bodies.Wastewater treatment plants (WWTPs) are significant sources of microplastics and PPCPs. It has been reported that treated sewage may still contain viable bacteria and ARGs, which then find their way into rivers and oceans (Raju *et al.*, 2023).

Agricultural practices often lead to runoff of fertilizers, pesticides, and other contaminants including microplastics. The runoff introduced antibiotic residues in the adjacent water bodies which promoted resistant bacteria proliferation (Perković *et al.*, 2022).

Soil and agricultural systems

Application of biosolids and irrigation with contaminated water introduces microplastics and PPCPs into soils. Biosolids, treated sewage sludge, applied into soils and irrigation using contaminated water, introduces microplastics and PPCPs. This process has immense implications for soil microbiomes that can develop resistance and may be transferred to plant-associated or human-pathogenic bacteria.

Biosolids usually carry residual antibiotics and ARGs from human waste. Once applied to agricultural fields, they introduce both microplastics and PPCPs into the soil ecosystem (Pozzebon *et al.*, 2023). Soil microbiomes exposed to these pollutants develop resistance, which can transfer to plant-associated or human-pathogenic bacteria.

Evidence of AMR amplification by microplastics and PPCPs

The interaction between microplastics and PPCPs especially contributes to the amplification of AMR. The amplification occurs through various mechanisms, as stated below.

Studies on antibiotic adsorption

Adsorption of antibiotics on microplastics follows a multilayer chemical adsorption process. This mechanism is governed by a combination of physical and chemical interactions.

Research has shown that tetracycline and ciprofloxacin antibiotics can be adsorbed strongly onto microplastics, especially on polyethylene (PE) and polyvinyl chloride (PVC). Such adsorption creates hotspots for antibiotic-resistant bacteria (ARB), allowing the survival and multiplication of such bacteria in contaminated environments (Tong, 2023).

ARG enrichment in biofilms

ARGs have always been observed in higher quantities in biofilms that form on microplastic surfaces compared to those in surrounding environments. Biofilm matrices are protective in nature and provide an opportunity for the aggregation and survival of ARGs.

Close proximity among resistant and non-resistant bacteria within biofilms promotes horizontal gene transfer, which has the capability of accelerating the dispersion of ARGs within the microbial community (Li, 2023).

Antibiotic co-resistance

Research has indicated that exposure to triclosan causes mutations in bacterial populations that give rise to resistance not only to triclosan itself but also to other antibiotics, including tetracycline and fluoroquinolone. El-Masry (2021) discovered that exposure to triclosan caused an increased minimum inhibitory concentration of several antibiotics in E. coli strains.

Implications for human and environmental health

Ecosystem disruption

The proliferation of antibiotic-resistant bacteria (ARB) affects the microbial ecosystems, thereby depleting the biodiversity and modified ecological functions, such as nutrient cycling. ARB may disrupt the balance of microbial communities in several ecosystems by dominant resistant strains overcoming susceptible strains leading to reduced microbial diversity (De Wit *et al.*, 2022).

Risk to human health

Microplastics provide a suitable substrate for microbial colonization, allowing formation of biofilms that can harbour a wide range of microorganisms, including ARB. The biofilm environment promotes horizontal gene transfer among bacteria that results in ARGs. The survival and proliferation of resistant bacteria in the aquatic environment is improved by the presence of microplastics. ARB and ARGs from microplastics can contaminate food and water supplies, increasing human exposure to resistant infections. The presence of resistant bacteria in the water sources is reported several times and, subsequently even, in the food chain if not treated properly (Iwu *et al.*, 2019; Ahmad *et al.*, 2024).

Ingestion of microplastic-laden seafood introduces ARGs into the human gut microbiome, potentially contributing to the spread of AMR as these bacteria can form a biofilm layer in the gut lining.The resistance can be obtained by spontaneous mutations in bacteria DNA. Such mutations may alter the target sites of antibiotics so that it is no longer active. For instance, alterations in penicillin-binding proteins are associated with resistance to beta-lactam antibiotics, including the penicillin and cephalosporins (Scoffone *et al.*, 2025).

Environmental persistence of PPCPs and microplastics

The persistence of pharmaceuticals and personal care products (PPCPs) and microplastics in the environment is a critical issue due to their resistance to natural degradation processes. Their prolonged presence affects ecosystems, biodiversity, and human health, exacerbating pollution and amplifying risks such as antimicrobial resistance (AMR).

Environmental persistence

Persistent contaminants

Once bound, PPCPs may persist in the environment for longer periods, reducing their natural degradation rates. The interaction between microplastics and PPCPs increases the persistence of both pollutants in the environment. Their long-lasting presence, coupled with their interactions and impacts, highlights the urgent need for integrated solutions to minimize their environmental footprint and mitigate associated risks.

Slower degradation

The hydrophobic interaction, $\pi - \pi$ interactions, and the electrostatic interactions between the microplastics and PPCPs makes them a stronger complex that enhances their persistence (Faltynkova, 2024). PPCPs adsorbed to microplastics are essentially protected from environmental degradation processes like photolysis and microbial degradation. Photolysis involves the breakdown of compounds by sunlight, and thus photolysis is impeded with PPCPs bound to microplastic surfaces. In this way, shielding PPCPs may prolong the half-life of these contaminants in the environment (Ajithkumar, 2024). The biofilm formed on the microplastic limits the exposure to degrading microbes that also slow down the degradation of PPCPs (Kumar *et al.*, 2024).

Sequestration in sediments

Microplastics tend to sink in aqueous environments and thus concentrate in sediments. When these microplastics adsorb PPCPs, they facilitate the transportation of contaminants to sequestered sediment layers. A recent study highlighted that microplastics-containing sediments and sorbed PPCPs have long-term reservoirs of these pollutants, thus extending their persistence in the environment (Castaño-Ortiz *et al.*, 2024).

Persistence of PPCPs

PPCPs include antibiotics, hormones, and synthetic chemicals that persist in the environment because they do not easily degrade in the natural processes. The persistence of such substances is significant to the ecosystems, biodiversity and human health due to increased pollution and enhanced problems such as AMR.

Factors contributing to persistence

Chemical stability

The chemical nature of PPCPs is quite crucial in their persistence. Chemical bonds that are quite stable, such as the fluorinated PPCPs which include fluoroquinolone antibiotics, are resistant to degradation. Hydrolysis and photolysis are examples of such degradation processes (Chen *et al.*, 2024).

Lipophilicity

Hydrophobic (lipophilic) PPCPs tend to adsorb on sediments and organic matters in aquatic environments. Through this adsorption process, their bioavailability towards the microbial degradation is reduced, and sometimes lead to accumulation in layers. It has been well found that lipophilicity plays a strong impact on the adsorption capacity of PPCPs onto microplastics further facilitating their persistence (Titov *et al.*, 2024).

Environmental conditions

Environmental factors like low temperatures, limited sunlight exposure and anaerobic conditions will slow down the degradation of PPCPs. For example, research has shown that PPCPs persistence is enhanced in in cold water temperatures because of reduced microbial activity (Shi *et al.*, 2023).

Pathways in the environment

Aquatic systems

PPCPs enter water bodies through wastewater effluents, agricultural runoff, and improper disposal. The wastewater treatment plants do not entirely remove PPCPs and allow them to be discharged into rivers and oceans, where they accumulate (Bavumiragira *et al.*, 2022). Persistent PPCPs accumulate in sediments and biofilms, acting as reservoirs of pollution.

Soil and groundwater

Land application of biosolids and irrigation with contaminated water introduces PPCPs into soils, where they may leach into groundwater.Shallow groundwater sources are most vulnerable to contamination by agricultural runoff and septic systems and thus cause long-term environmental contamination (Gyimah *et al., 2024*). Table 3 reviews the various examples of persistent PPCPs in different media.

Persistence of microplastics

The high persistence of microplastics in the environment is linked to their synthetic nature and chemical stability, coupled with their resistance to biodegradation. This level of persistence raises ecological and health concerns and thus in-depth research is needed on the factors associated with their persistence and also on the routes of their dispersal. Some examples of persistent microplastic and their environmental impacts are given in Table 4.

Factors contributing to persistence

Material composition

Common polymers such as polyethylene (PE), polypropylene (PP), and polystyrene (PS) are known to degrade extremely slowly. Their lifetimes can be estimated to range between decades and centuries. For instance, PE can last over 100 years in marine environments (Andrady, 2011). This is because the chemical structure of these polymers makes them resistant to natural degradation processes and hence tends to accumulate in ecosystems.

Size and surface area

The smaller microplastics, for example, nanoplastics, have a high surface area-to-volume ratio, which makes them more challenging to detect and degrade. Their small size allows them to evade many conventional waste management systems and increases their bioavailability to organisms. Studies have shown that smaller particles can be ingested by a wider range of organisms, leading to potential toxic effects and further dispersal in food webs (Patil *et al.*, 2022; Yarahmadi *et al.*, 2024). Aquatic invertebrates consume microplastics because they appear to be a similar size to plankton, disrupting its physiological functions (Witczak *et al.*, 2024).

Table 3. Examples of persistent PPCPs in various media

Category	PPCP compound	Media	Source	Reference
Antibiotic	Ciprofloxacin	Surface water	Wastewater effluents, agricultural runoff	Sarafraz *et al.*, 2022
	Sulfamethoxazole	Groundwater	Septic systems, land application of biosolids	Chen and Akhtar, 2022
	Tetracycline	Soil	Agricultural runoff, biosolid application	Matamoros *et al.*, 2022
Endocrine disruptors	17α-ethinylestradiol	Surface and drinking water	Wastewater treatment plants, agricultural runoff	Rastkari *et al.*, 2023
	Bisphenol A	Groundwater	Land application of biosolids, agricultural runoff	Dueñas-Moreno *et al.*, 2022
Non-biodegradable fragrances	Synthetic musk - Galaxolide	Soil	Landfill leachate, agricultural runoff	Chakraborty *et al.*, 2023
	Linalyl Acetate	Air	Personal care products, household cleaning products	Rádis-Baptista, 2023

Table 4. Examples of persistent microplastics

Persistent microplastic	Common uses	Environmental impact	Reference
Polyethylene (PE)	Packaging materials	Dominates plastic debris; persists for decades; adsorbs pollutants	Wojnowska *et al.*, 2022
Polypropylene (PP)	Food containers	Commonly found in marine debris; slow degradation leads to long-term environmental risks	Dey *et al.*, 2024
Polystyrene (PS)	Disposable cups, insulation	Accumulates in aquatic environments; potential toxic effects on marine life	Gupta *et al.*, 2022
Polyester Fibers	Textiles	Shed during washing; accumulate in aquatic systems; contribute to microplastic pollution	Šaravanja *et al.*, 2022

Environmental conditions

Environmental factors greatly impact the degradation rates of microplastics. Though photodegradation is triggered by UV, low light such as deep oceans or soils does not cause much degradation. Scientific studies show that microplastics buried in sediments or submerged in dark waters could be intact for many years (Zhang *et al.*, 2024).

Pathways in the environment

Aquatic systems

Microplastics can accumulate on the surface of the ocean, in sediments, and along shorelines. These can travel through currents to the remotest parts of the Earth, including the Arctic, and alter pristine ecosystems (Mishra *et al.*, 2021).

Terrestrial systems

Soil contamination occurs through agricultural practices that involve plastic waste or tire wear. Microplastics may persist in soils for decades, affecting soil structure and function. Research has shown that microplastics can alter microbial communities in soils, potentially impacting nutrient cycling and plant health (Aralappanavar *et al.*, 2024).

Atmospheric transport

Microplastics are also transported by wind and rain, which can transport them to remote locations. Atmospheric deposition can cause microplastic contamination in pristine environments, such as mountainous and polar regions (Han *et al.*, 2023).

CONCLUSION

Microplastics increase the persistence and toxicity of contaminants, such as PPCPs. PPCPs adsorb onto the microplastic surfaces through hydrophobic forces, Vander Waals interactions, hydrogen bonding, and electrostatic attractions. Environmental factors such as pH, salinity and temperature affect adsorption and desorption processes. Biofilm formation on microplastics entraps more of these contaminants, increasing bioavailability. This leads to bioaccumulation and toxic effects on organisms and even on human health. The complex of microplastics-PPCPs poses significant ecological challenges that must be addressed to prevent their spread and impact. The widespread dispersal of contaminants and their toxic effects in food webs indicates a need for better waste management and mitigation strategies.

MITIGATION STRATEGIES

Policy and regulatory frameworks

Some regulatory measures have been implemented to reduce the environmental impact of microplastic-PPCPs contamination, with varying results across the globe. The microbead ban in the European Union and the microbead-free Water Act in United States are some examples of how to reduce the primary microplastic contamination (Kukkola *et al.*, 2024; Xu, 2024). However, treating secondary microplastics caused by plastic breakdown remains challenging.

Public awareness and sustainable behaviour

Public education campaigns play a vital role in promoting sustainable behaviours. Reducing plastic consumption with biodegradable alternatives has the potential to significantly reduce the microplastic pollution. Improvements in ecologically friendly PPCP formulations also lead to the creation of safer medicinal substances with a less environmental footprint.

FUTURE INSIGHTS LEADING TO RESEARCH

Desorption dynamics: Understanding conditions that trigger the release of PPCPs from microplastics is critical for assessing real-world risks.

Long-term impacts: The cumulative effects of microplastic-PPCP complexes on ecosystems and food chains remain poorly understood.

Analytical limitations: Detecting and quantifying PPCPs on microplastics requires advanced, standardized analytical techniques.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the financial support given by the MHRD-RUSA 2.0 Biological Sciences, to carry out the research work.

REFERENCES

Ahmad O, Ahmed S, Khan F, Upmanyu K, Saif M, Haq QMR. 2024. Antibiotic resistant bacteria colonising microplastics in the aquatic environment: an emerging challenge. Discover Sustainability **5**(1), 1–16. DOI: 10.1007/s43621-024-00722-4

Ajithkumar V, Philomina A, Meena K, Pothiaraj G, Dey D, Sowbaranika M, Varalakshmi P. 2024. Insights of recent developments in microplastics pollution and its degradation in wastewater and other environment. Journal of the Taiwan Institute of Chemical Engineers **105504**. DOI: 10.1016/j.jtice.2024.105504

Alfaro-Núñez A, Astorga D, Cáceres-Farías L, Bastidas L, Soto Villegas C, Macay K, Christensen JH. 2021. Microplastic pollution in seawater and marine organisms across the tropical eastern Pacific and Galápagos. Scientific Reports **11**(1), 6424. DOI: 10.1038/s41598-021-85939-3

Andrady AL. 2011. Microplastics in the marine environment. Marine Pollution Bulletin **62(8)**, 1596–1605. DOI: 10.1016/j.marpolbul.2011.05.030

Anthony J, Varalakshmi S, Kumar Sekar A, Thalavai Sivasankarasubbiah K, Harikrishnan T, Rangamaran VR, Ramalingam K. 2024. Microplastics pollution in Indian marine environment: sources, effects and solutions. Frontiers in Marine Science **11**, 1512802. DOI: 10.3389/fmars.2024.1512802

Aralappanavar VK, Mukhopadhyay R, Yu Y, Liu J, Bhatnagar A, Praveena SM, Sarkar B. 2024. Effects of microplastics on soil microorganisms and microbial functions in nutrients and carbon cycling – a review. Science of the Total Environment **171435**. DOI: 10.1016/j.scitotenv.2024.171435

Ašmonaitė G, Tivefälth M, Westberg E, Magnér J, Backhaus T, Carney Almroth B. 2020. Microplastics as a vector for exposure to hydrophobic organic chemicals in fish: A comparison of two polymers and silica particles spiked with three model compounds. Frontiers in Environmental Science **8**, 87. DOI: 10.3389/fenvs.2020.00087

Atugoda T, Vithanage M, Wijesekaran H, Bolan N, Sarmah AK, Bank MS, Ok YS. 2021. Interactions between microplastics, pharmaceuticals and personal care products: implications for vector transport. Environment International **149**, 106367. DOI: 10.1016/j.envint.2020.106367

Barus BS, Purwiyanto AIS, Suteja Y. 2023. Microplastic and heavy metal interactions (adsorption and desorption) at different salinities. BIO Web of Conferences **74**, 05004. DOI: 10.1051/bioconf/20237405004

Bavumiragira JP, Yin H. 2022. Fate and transport of pharmaceuticals in water systems: a processes review. Science of the Total Environment **823**, 153635. DOI: 10.1016/j.scitotenv.2022.153635

Bhagwat KP, Rodrigue D, Romero-Zerón L. 2024. Effective removal of microplastic particles from wastewater using hydrophobic bio-substrates. Pollutants **4**(2), 231–250. DOI: 10.3390/pollutants4020015

Bhuyan MS. 2022. Effects of microplastics on fish and in human health. Frontiers in Environmental Science **10**, 827289. DOI: 10.3389/fenvs.2022.827289

Bora SS, Gogoi R, Sharma MR, Anshu Borah MP, Deka P, Teli AB. 2024. Microplastics and human health: unveiling the gut microbiome disruption and chronic disease risks. Frontiers in Cellular and Infection Microbiology **14**, 1492759. DOI: 10.3389/fcimb.2024.1492759

Boxall ABA. 2012. New and emerging water pollutants arising from agriculture.

Castaño-Ortiz JM, Romero F, Cojoc L, Barceló D, Balcázar JL, Rodríguez-Mozaz S, Santos L H M L M. 2024. Accumulation of polyethylene microplastics in river biofilms and effect on the uptake, biotransformation and toxicity of the antimicrobial triclosan. Environmental Pollution **344**, 123369. DOI: 10.1016/j.envpol.2024.123369

Chakraborty A, Adhikary S, Bhattacharya S, Dutta S, Chatterjee S, Banerjee D, Rajak P. 2023. Pharmaceuticals and personal care products as emerging environmental contaminants: prevalence, toxicity, and remedial approaches. ACS Chemical Health & Safety **30**(6), 362–388. DOI: 10.1021/acs.chas.3c00071

Chen H, Akhtar L. 2022. Fate and transport of pharmaceuticals and personal care products in soils and groundwater. In Emerging Contaminants in Soil and Groundwater Systems (pp. 49–82). Elsevier. DOI: 10.1016/b978-0-12-824088-5.00004-5

Chen Q, Shi G, Revell LE, Zhang J, Zuo C, Wang D, Mitrano DM. 2023. Long-range atmospheric transport of microplastics across the southern hemisphere. Nature Communications **14**(1), 7898. DOI: 10.1038/s41467-023-43695-0

Chen X, Chen CE, Cheng S, Sweetman AJ. 2024. Bisphenol A sorption on commercial polyvinyl chloride microplastics: effects of UV-aging, biofilm colonization and additives on plastic behavior in the environment. Environmental Pollution **124218**. DOI: 10.1016/j.envpol.2024.124218

Chen X, Song Y, Ling C, Shen Y, Zhan X, Xing B. 2024. Fate of emerging antibiotics in soil-plant systems: a case on fluoroquinolones. Science of the Total Environment **175487**. DOI: 10.1016/j.scitotenv.2024.175487

Cortés-Arriagada D, Ortega DE. 2023. Interaction mechanism of triclosan on pristine microplastics. Science of the Total Environment **891**, 164470. DOI: 10.1016/j.scitotenv.2023.164470

Costa E, Gambardella C, Piazza V, Vassalli M, Sbrana F, Lavorano S, Faimali M. 2020. Microplastics ingestion in the ephyra stage of *Aurelia* sp. triggers acute and behavioral responses. Ecotoxicology and Environmental Safety **189**, 109983. DOI: 10.1016/j.ecoenv.2019.109983

Darabi M, Majeed H, Diehl A, Norton J, Zhang Y. 2021. A review of microplastics in aquatic sediments: occurrence, fate, transport, and ecological impact. Current Pollution Reports **7**, 40–53. DOI: 10.1007/s40726-020-00171-3

Das S, Ray NM, Wan J, Khan A, Chakraborty T, Ray MB. 2017. Micropollutants in wastewater: fate and removal. Physico-Chemical Wastewater Treatment and Resource Recovery **75**.

De Wit G, Svet L, Lories B, Steenackers HP. 2022. Microbial interspecies interactions and their impact on the emergence and spread of antimicrobial resistance. Annual Review of Microbiology **76**(1), 179–192.
DOI: 10.1146/annurev-micro-041320-031627

Dey S, Veerendra GTN, Babu PA, Manoj AP, Nagarjuna K. 2024. Degradation of plastics waste and its effects on biological ecosystems: a scientific analysis and comprehensive review. Biomedical Materials & Devices **2**(1), 70–112.
DOI: 10.1007/s44174-023-00085-w

Dick L, Batista PR, Zaby P, Manhart G, Kopatz V, Kogler L, Hollóczki O. 2024. The adsorption of drugs on nanoplastics has severe biological impact. Scientific Reports **14**(1), 25853. DOI: 10.1038/s41598-024-75785-4

Donkers JM, Höppener EM, Grigoriev I, Will L, Melgert BN, van der Zaan B, Kooter IM. 2022. Advanced epithelial lung and gut barrier models demonstrate passage of microplastic particles. Microplastics and Nanoplastics **2**(1), 6. DOI: 10.1186/s43591-021-00024-w

Du J, Huang W, Pan Y, Xu S, Li H, Jin M, Liu Q. 2024. Ecotoxicological effects of microplastics combined with antibiotics in the aquatic environment: recent developments and prospects. Environmental Toxicology and Chemistry **43**(9), 1950–1961. DOI: 10.1002/etc.5950

Du J, Zhan L, Zhang G, Zhou Q, Wu W. 2024. Antibiotic sorption onto MPs in terrestrial environment: a critical review of the transport, bioaccumulation, ecotoxicological effects and prospects. Drug and Chemical Toxicology, 1–15.
DOI: 10.1080/01480545.2024.2433075

Ducoli S, Kalčíková G, Velimirovic M, Depero LE, Federici S. 2025. Production, characterization, and toxicology of environmentally relevant nanoplastics: a review. Environmental Chemistry Letters, 1–27.
DOI: 10.1007/s10311-024-01810-7

Dueñas-Moreno J, Mora A, Cervantes-Avilés P, Mahlknecht J. 2022. Groundwater contamination pathways of phthalates and bisphenol A: origin, characteristics, transport, and fate – a review. Environment International **170**, 107550.
DOI: 10.1016/j.envint.2022.107550

Dutta S, Sengupta P, Bagchi S, Chhikara BS, Pavlík A, Sláma P, Roychoudhury S. 2023. Reproductive toxicity of combined effects of endocrine disruptors on human reproduction. Frontiers in Cell and Developmental Biology **11**, 1162015.
DOI: 10.3389/fcell.2023.1162015

El-Masry EA, Taha AE, Ajlan SE. 2021. The effect of triclosan adaptation on antimicrobial resistance among clinical *Escherichia coli* isolates from Egyptian patients. Journal of Pure & Applied Microbiology **15**(4).
DOI: 10.22207/jpam.15.4.64

Esterhuizen M, Monticelli M, Lee SA, Kim Y, Pflugmacher S, Kim YJ. 2024. Oxidative stress status and antioxidative responses in neonate versus adult *Daphnia magna* exposed to polystyrene leachate. Toxicology and Environmental Health Sciences **16**(2), 171–179. DOI: 10.1007/s13530-024-00211-1

Fakayode SO, Mehari TF, Fernand Narcisse VE, Grant C, Taylor ME, Baker GA, Anum D. 2024. Microplastics: challenges, toxicity, spectroscopic and real-time detection methods. Applied Spectroscopy Reviews, 1–95. DOI: 10.1080/05704928.2024.2311130

Faltynkova A, Deschênes CE, Zolich A, Wagner M, Johansen TA, Johnsen G. 2024. Use of an uncrewed surface vehicle and near-infrared hyperspectral imaging for sampling and analysis of aquatic microplastics. Marine Pollution Bulletin **201**, 116214. DOI: 10.1016/j.marpolbul.2024.116214

Gani A, Pathak S, Hussain A, Shukla AK, Chand S. 2024. Emerging pollutant in surface water bodies: a review on monitoring, analysis, mitigation measures and removal technologies of micro-plastics. Environmental Geochemistry and Health **46**(7), 1–31.
DOI: 10.1007/s10653-024-01992-7

Gao C, Xu B, Li Z, Wang Z, Huang S, Jiang Z, Yang H. 2025. From plankton to fish: the multifaceted threat of microplastics in freshwater environments. Aquatic Toxicology **107242**.
DOI: 10.1016/j.aquatox.2025.107242

Gigault J, Davranche M. 2025. Nanoplastics in focus: exploring interdisciplinary approaches and future directions. NanoImpact **100544**.
DOI: 10.1016/j.impact.2025.100544

Gunaalan K, Almeda R, Vianello A, Lorenz C, Iordachescu L, Papacharalampos K, Vollertsen J. 2024. Does water column stratification influence the vertical distribution of microplastics? Environmental Pollution **340**, 122865.
DOI: 10.1016/j.envpol.2023.122865

Gupta C, Kaushik S, Jain S, Dhanwani I, Garg S, Paul A, Gupta N. 2022. Bioaccumulation and toxicity of polystyrene nanoplastics on marine and terrestrial organisms with possible remediation strategies: a review. Environmental Advances **8**, 100227.
DOI: 10.1016/j.envadv.2022.100227

Gupta V, Vimalkumar K, Sanyal P, Paul M, Acharya A, Bakshi S, Majumdar N. 2024. Occurrences, distribution and sources of pharmaceuticals and personal care products (PPCPs) in the mangrove-dominated estuaries in the central part of the Indian Sundarbans, a world heritage site.
DOI: 10.31223/x5f10s

Gyimah R, Lebu S, Owusu-Frimpong I, Semiyaga S, Salzberg A, Manga M. 2024. Effluents from septic systems and impact on groundwater contamination: a systematic review. Environmental Science and Pollution Research, 1–21. DOI: 10.1007/s11356-024-35385-1

Hai N, Liu X, Li Y, Kong F, Zhang Y, Fang S. 2020. Effects of microplastics on the adsorption and bioavailability of three strobilurin fungicides. ACS Omega **5**(47), 30679–30686.
DOI: 10.1021/acsomega.0c04787

Hamed M, Martyniuk CJ, Naguib M, Lee JS, Sayed AEDH. 2022. Neurotoxic effects of different sizes of plastics (nano, micro, and macro) on juvenile common carp (*Cyprinus carpio*). Frontiers in Molecular Neuroscience **15**, 1028364.
DOI: 10.3389/fnmol.2022.1028364

Han B, Yacoub M, Li A, Nicholson K, Gruver J, Neumann K, Sharma S. 2023. Human activities increased microplastics contamination in the Himalaya mountains. Hydrology **11**(1), 4.
DOI: 10.3390/hydrology11010004

Han X, Wang S, Yu X, Vogt RD, Feng J, Zhai L, Ma W, Zhu L, Lu X. 2021. Kinetics and size effects on adsorption of Cu(II), Cr(III), and Pb(II) onto polyethylene, polypropylene, and polyethylene terephthalate microplastic particles. Frontiers in Marine Science **8**. DOI: 10.3389/fmars.2021.785146

Hashem HM, El-Shaheny R, El-Maghrabey MH. 2024. Microplastics as an ecological vector transport for pharmaceuticals: insights into the interaction mechanisms. In Microplastics and Pollutants: Interactions, Degradations and Mechanisms (pp. 265–297). Cham: Springer Nature Switzerland.
DOI: 10.1007/978-3-031-54565-8_12

Heinze WM, Mitrano DM, Lahive E, Koestel J, Cornelis G. 2021. Nanoplastic transport in soil via bioturbation by *Lumbricus terrestris*. Environmental Science & Technology **55**(24), 16423–16433.
DOI: 10.1021/acs.est.1c05614

Honarmandrad Z, Kaykhaii M, Gębicki J. 2023. Microplastics removal from aqueous environment by metal organic frameworks. BMC Chemistry **17**, 122. DOI: 10.1186/s13065-023-01032-y

Hong X. 2025. Combined molecular toxicity mechanism of emerging pollutant mixtures. In Toxicological Assessment of Combined Chemicals in the Environment, 195–208.
DOI: 10.1002/9781394158355.ch12

Isaeva VI, Vedenyapina MD, Kurmysheva AY, Weichgrebe D, Nair RR, Nguyen NPT, Kustov LM. 2021. Modern carbon-based materials for adsorptive removal of organic and inorganic pollutants from water and wastewater. Molecules **26**(21), 6628. DOI: 10.3390/molecules26216628

Iwu CD, Okoh AI. 2019. Preharvest transmission routes of fresh produce associated bacterial pathogens with outbreak potentials: a review. International Journal of Environmental Research and Public Health **16**(22), 4407.
DOI: 10.3390/ijerph16224407

Jahan I, Chowdhury G, Rafi S, Ashab Md A, Sarker M, Chakraborty A, Couetard N, Kabir MA, Hossain MA, Iqbal MM. 2024. Assessment of dietary polyvinylchloride, polypropylene and polyethylene terephthalate exposure in Nile tilapia, *Oreochromis niloticus*: bioaccumulation, and effects on behaviour, growth, hematology and histology. Environmental Pollution **345**, 123548.
DOI: 10.1016/j.envpol.2024.123548

Jiao Y, Zhou A, Zhang D, Chen M, Wan L. 2024. Distinct microbial community structures formed on the biofilms of PLA and PP, influenced by physicochemical factors of sediment and polymer types in a 60-day indoor study. Frontiers in Environmental Science **12**, 1452523.
DOI: 10.3389/fenvs.2024.1452523

Joo SH, Liang Y, Kim M, Byun J, Choi H. 2021. Microplastics with adsorbed contaminants: mechanisms and treatment. Environmental Challenges **3**, 100042. DOI: 10.1016/j.envc.2021.100042

Kibuye FA, Gall HE, Elkin KR, Ayers B, Veith TL, Miller M, Jacob S, Hayden KR, Watson JE, Elliott HA. 2019. Fate of pharmaceuticals in a spray-irrigation system: from wastewater to groundwater. Science of the Total Environment **654**, 197–208.
DOI: 10.1016/j.scitotenv.2018.10.442

Kolpin DW, Furlong ET, Meyer MT, Thurman EM, Zaugg SD, Barber LB, Buxton HT. 2002. Pharmaceuticals, hormones, and other organic wastewater contaminants in US streams, 1999–2000: a national reconnaissance. Environmental Science & Technology **36**(6), 1202–1211. DOI: 10.1021/es011055j

Kukkola A, Chetwynd AJ, Krause S, Lynch I. 2024. Beyond microbeads: examining the role of cosmetics in microplastic pollution and spotlighting unanswered questions. Journal of Hazardous Materials, 135053.

Kumar N, Lamba M, Pachar AK, Yadav S, Acharya A. 2024. Microplastics – a growing concern as carcinogens in cancer etiology: emphasis on biochemical and molecular mechanisms. Cell Biochemistry and Biophysics, 1–13. DOI: 10.1007/s12013-024-01436-0

Kumar P, Chaudhary S, Bhalla A. 2024. Occurrence and fate of emerging contaminants with microplastics: current scenario, sources and effects. In Occurrence, Distribution and Toxic Effects of Emerging Contaminantsx (pp. 58–100).
DOI: 10.1201/9781003335757-4

Lee Y, Cho J, Sohn J, Kim C. 2023. Health effects of microplastic exposures: current issues and perspectives in South Korea. Yonsei Medical Journal **64**(5), 301. DOI: 10.3349/ymj.2023.0048

Lenaker PL, Baldwin AK, Corsi SR, Mason SA, Reneau PC, Scott JW. 2019. Vertical distribution of microplastics in the water column and surficial sediment from the Milwaukee River Basin to Lake Michigan. Environmental Science & Technology **53**(21), 12227–12237. DOI: 10.1021/acs.est.9b03850

Leng Y, Wang W, Cai H, Chang F, Xiong W, Wang J. 2023. Sorption kinetics, isotherms and molecular dynamics simulation of 17β-estradiol onto microplastics. Science of the Total Environment **858**, 159803. DOI: 10.1016/j.scitotenv.2022.159803

Li C, Jiang B, Guo J, Sun C, Shi C, Huang S, Liu W, Wu C, Zhang Y. 2022. Aging process of microplastics in the aquatic environments: aging pathway, characteristic change, compound effect, and environmentally persistent free radicals formation. Water **14**(21), 3515. DOI: 10.3390/w14213515

Li J, Huang X, Hou Z, Ding T. 2022. Sorption of diclofenac by polystyrene microplastics: kinetics, isotherms and particle size effects. Chemosphere **290**, 133311. DOI: 10.1016/j.chemosphere.2021.133311

Li J, Yu S, Chen X, Cai Y, Cui M. 2023. Highly enhanced adsorption of antibiotics on aged polyamide microplastics. Colloids and Surfaces A: Physicochemical and Engineering Aspects **658**, 130690. DOI: 10.1016/j.colsurfa.2022.130690

Li J, Zhang K, Zhang H. 2018. Adsorption of antibiotics on microplastics. Environmental Pollution **237**, 460–467. DOI: 10.1016/j.envpol.2018.02.050

Li Q, Jiang L, Feng J, Wang X, Wang X, Xu X, Chu W. 2024. Aged polystyrene microplastics exacerbate alopecia associated with tight junction injuries and apoptosis via oxidative stress pathway in skin. Environment International **186**, 108638. DOI: 10.1016/j.envint.2024.108638

Li S, Ondon BS, Ho SH, Zhou Q, Li F. 2023. Drinking water sources as hotspots of antibiotic-resistant bacteria (ARB) and antibiotic resistance genes (ARGs): occurrence, spread, and mitigation strategies. Journal of Water Process Engineering **53**, 103907. DOI: 10.1016/j.jwpe.2023.103907

Li Z, Junaid M, Chen G, Wang J. 2022. Interactions and associated resistance development mechanisms between microplastics, antibiotics and heavy metals in the aquaculture environment. Reviews in Aquaculture **14**(2), 1028–1045. DOI: 10.1111/raq.12639

Liang S, Wang K, Wang K, Wang T, Guo C, Wang W, Wang J. 2023. Adsorption behavior of diclofenac on polystyrene and poly (butylene adipate-co-terephthalate) microplastics: influencing factors and adsorption mechanism. Langmuir **39**(34), 12216–12225. DOI: 10.1021/acs.langmuir.3c01536

Liang Y, Ying C, Zhu J, Zhou Q, Sun K, Tian Y, Li J. 2023. Effects of salinity, pH, and Cu(II) on the adsorption behaviors of tetracycline onto polyvinyl chloride microplastics: a site energy distribution analysis. Water **15**(10), 1925. DOI: 10.3390/w15101925

Liu R, Wang Z, Ling M, Zhang K, Xu W, Xu Z, Huang X, Qiao Y, Luo Y, Zhang W, Grossart H-P, Luo Z. 2025. Dynamics of plastisphere microbial communities in mangrove sediments and their potential impact on N-cycling. International Biodeterioration & Biodegradation **196**, 105929. DOI: 10.1016/j.ibiod.2024.105929

Liu X, Wei H, Ahmad S, Wang R, Gao P, Chen J, Song Y, Liu C, Ding N, Tang J. 2024. Effects and mechanism of microplastics on abundance and transfer of antibiotic resistance genes in the environment – a critical review. Critical Reviews in Environmental Science and Technology **54**(24), 1852–1874. DOI: 10.1080/10643389.2024.2368758

Liu Y, Liu X, Dong W, Zhang L, Kong Q, Wang W. 2017. Efficient adsorption of sulfamethazine onto modified activated carbon: a plausible adsorption mechanism. Scientific Reports **7**, 12437. DOI: 10.1038/s41598-017-12805-6

Liu Y, Wu Y, Chen Y, Zhang P, Zheng X. 2024. Capturer of emerging contaminants: potentials and perspectives of amyloid protein nanofibrils as the novel adsorbents. Chemical Engineering Journal, 152819.

Liu Z, Gan Y, Luo J, Luo X, Ding C, Cui Y. 2025. Current status of emerging contaminant models and their applications concerning the aquatic environment: a review. Water **17**(1), 85. DOI: 10.3390/w17010085

Lu J, Wu J, Gong L, Cheng Y, Yuan Q, He Y. 2022. Combined toxicity of polystyrene microplastics and sulfamethoxazole on zebrafish embryos. Environmental Science and Pollution Research, 1–10. DOI: 10.1007/s11356-021-17198-8

Maillard JY, Pascoe M. 2024. Disinfectants and antiseptics: mechanisms of action and resistance. Nature Reviews Microbiology **22**(1), 4–17. DOI: 10.1038/s41579-023-00958-3

Marathe NP, Bank MS. 2022. The microplastic-antibiotic resistance connection. In Microplastic in the environment: pattern and process. Environmental Contamination Remediation and Management. Springer, Cham, 311–322. DOI: 10.1007/978-3-030-78627-4_9

Marcu D, Keyser S, Petrik L, Fuhrimann S, Maree L. 2023. Contaminants of emerging concern (CECs) and male reproductive health: challenging the future with a double-edged sword. Toxics **11**(4), 330. DOI: 10.3390/toxics11040330

Martín J, Santos JL, Aparicio I, Alonso E. 2022. Microplastics and associated emerging contaminants in the environment: analysis, sorption mechanisms and effects of co-exposure. Trends in Environmental Analytical Chemistry **35**, e00170. DOI: 10.1016/j.teac.2022.e00170

Matamoros V, Casas ME, Pastor E, Tadić Đ, Cañameras N, Carazo N, Bayona JM. 2022. Effects of tetracycline, sulfonamide, fluoroquinolone, and lincosamide load in pig slurry on lettuce: agricultural and human health implications. Environmental Research **215**, 114237. DOI: 10.1016/j.envres.2022.114237

Matei E, Covaliu-Mierla CI, Ţurcanu AA, Râpă M, Predescu AM, Predescu C. 2022. Multifunctional membranes—A versatile approach for emerging pollutants removal. Membranes **12**(1), 67.

Meadows JR. 2019. Early life stress and pharmaceutical pollutants: developmental toxicity of emerging aquatic contaminants in a model terrestrial species. East Carolina University.

Mei W, Chen G, Bao J, Song M, Li Y, Luo C. 2020. Interactions between microplastics and organic compounds in aquatic environments: a mini review. Science of The Total Environment **736**, 139472. DOI: 10.1016/j.scitotenv.2020.139472

Mishra AK, Singh J, Mishra PP. 2021. Microplastics in polar regions: an early warning to the world's pristine ecosystem. Science of The Total Environment **784**, 147149. DOI: 10.1016/j.scitotenv.2021.147149

Nguyen MK, Rakib MRJ, Lin C, Hung NTQ, Le VG, Nguyen HL, Malafaia G, Idris AM. 2023. A comprehensive review on ecological effects of microplastic pollution: an interaction with pollutants in the ecosystems and future perspectives. TrAC Trends in Analytical Chemistry, 117294. DOI: 10.1016/j.trac.2023.117294

Pan T, Liao H, Yang F, Sun F, Guo Y, Yang H, Feng D, Zhou X, Wang Q. 2023. Review of microplastics in lakes: sources, distribution characteristics, and environmental effects. Carbon Research **2(1)**, 25. DOI: 10.1007/s44246-023-00057-1

Partridge SR, **Kwong SM**, **Firth N**, **Jensen SO.** 2018. Mobile genetic elements associated with antimicrobial resistance. Clinical Microbiology Reviews **31**(4), 10-1128. DOI: 10.1128/cmr.00088-17

Patil SM, **Rane NR**, **Bankole PO**, **Krishnaiah P**, **Ahn Y**, **Park YK**, **Yadav KK**, **Amin MA**, **Jeon BH.** 2022. An assessment of micro- and nanoplastics in the biosphere: a review of detection, monitoring, and remediation technology. Chemical Engineering Journal **430**, 132913. DOI: 10.1016/j.cej.2021.132913

Patterson J. 2025. Accumulation of microplastics in relation to the sediment grain size distribution in seagrass meadows in the coastal areas of Tuticorin, southeast coast of India. Marine Pollution Bulletin **212**, 117557. DOI: 10.1016/j.marpolbul.2025.117557

Pérez-Lucas G, **Navarro S.** 2024. How pharmaceutical residues occur, behave, and affect the soil environment. Journal of Xenobiotics **14**(4), 1343–1377. DOI: 10.3390/jox14040076

Perković S, **Paul C**, **Vasić F**, **Helming K.** 2022. Human health and soil health risks from heavy metals, micro(nano)plastics, and antibiotic resistant bacteria in agricultural soils. Agronomy **12**(12), 2945. DOI: 10.3390/agronomy12122945

Picó Y, **Alvarez-Ruiz R**, **Alfarhan AH**, **El-Sheikh MA**, **Alshahrani HO**, **Barceló D.** 2020. Pharmaceuticals, pesticides, personal care products and microplastics contamination assessment of Al-Hassa irrigation network (Saudi Arabia) and its shallow lakes. Science of The Total Environment **701**, 135021.
DOI: 10.1016/j.scitotenv.2019.135021

Pinto SZ, **Aneck-Hahn N.** 2025. Effect of in vitro exposure of first-line antiretrovirals on healthy human spermatozoa on kinematics and motility. International Urology and Nephrology, 1–21.
DOI: 10.1007/s11255-024-04340-x

Pozzebon EA, **Seifert L.** 2023. Emerging environmental health risks associated with the land application of biosolids: a scoping review. Environmental Health **22**(1), 57. DOI: 10.1186/s12940-023-01008-4

Prata JC, **Da Costa JP**, **Lopes I**, **Duarte AC**, **Rocha-Santos T.** 2020. Environmental exposure to microplastics: an overview on possible human health effects. Science of The Total Environment **702**, 134455.

Radford F, **Horton AA**, **Felgate S**, **Lichtschlag A**, **Hunt J**, **Andrade V**, **Sanders R**, **Evans C.** 2024. Factors influencing microplastic abundances in the sediments of a seagrass-dominated tropical atoll. Environmental Pollution **357**, 124483. DOI: 10.1016/j.envpol.2024.124483

Rádis-Baptista G. 2023. Do synthetic fragrances in personal care and household products impact indoor air quality and pose health risks?. Journal of Xenobiotics **13**(1), 121–131. DOI: 10.3390/jox13010010

Rai PK, **Sonne C**, **Brown RJC**, **Younis SA**, **Kim KH.** 2022. Adsorption of environmental contaminants on micro- and nano-scale plastic polymers and the influence of weathering processes on their adsorptive attributes. Journal of Hazardous Materials **427**, 127903. DOI: 10.1016/j.jhazmat.2021.127903

Raju M, **Gandhimathi R**, **Nidheesh PV.** 2023. The cause, fate and effect of microplastics in freshwater ecosystem: ways to overcome the challenge. Journal of Water Process Engineering **55**, 104199.
DOI: 10.1016/j.jwpe.2023.104199

Rastkari N, **Ahmadkhaniha R**, **Beikmohammadi M**, **Yousefi SS.** 2023. Assessment of emerging endocrine-disrupting compounds, namely estrone, 17-beta-estradiol, estriol, and 17-alpha-ethinyl estradiol, in the drinking water piping network of Tehran. Water Supply **23**(10), 4015–4030.
DOI: 10.2166/ws.2023.239

Reis LDPG, Lora-Benítez AJ, Molina-López AM, Mora-Medina R, Ayala-Soldado N, Moyano-Salvago MDR. 2022. Evaluation of the toxicity of bisphenol A in reproduction and its effect on fertility and embryonic development in the zebrafish (Danio rerio). International Journal of Environmental Research and Public Health **19**(2), 962. DOI: 10.3390/ijerph19020962

Ribeiro F, Pavlaki MD, Loureiro S, Sarmento RA, Soares AM, Tourinho PS. 2023. Systematic review of nano- and microplastics' (NMP) influence on the bioaccumulation of environmental contaminants: Part II—Freshwater organisms. Toxics **11**(6), 474. DOI: 10.3390/toxics11060474

Rozman U, Klun B, Kuljanin A, Skalar T, Kalčíková G. 2023. Insights into the shape-dependent effects of polyethylene microplastics on interactions with organisms, environmental aging, and adsorption properties. Scientific Reports **13**, 22147. DOI: 10.1038/s41598-023-49175-1

Santana GB, Conceição KG, Silva EM, Diaz GZ, Oliveira JT, Oliveira AG, Melo DQ, Nascimento RF, Prola LDT, Liz MV, Coral LAA, Campos OS, Vidal CB. 2025. Photoaging effects on polyethylene microplastics: structural changes and chlorpyrifos adsorption. Marine Environmental Research **203**, 106844.
DOI: 10.1016/j.marenvres.2024.106844

Sarafraz M, Ali S, Sadani M, Heidarinejad Z, Bay A, Fakhri Y, Mousavi Khaneghah A. 2022. A global systematic, review-meta analysis and ecological risk assessment of ciprofloxacin in river water. International Journal of Environmental Analytical Chemistry **102**(17), 5106–5121.
DOI: 10.1080/03067319.2020.1791330

Šaravanja A, Pušić T, Dekanić T. 2022. Microplastics in wastewater by washing polyester fabrics. Materials **15**(7), 2683.
DOI: 10.3390/ma15072683

Scoffone VC, Trespidi G, Barbieri G, Arshad A, Israyilova A, Buroni S. 2025. The evolution of antimicrobial resistance in Acinetobacter baumannii and new strategies to fight it. Antibiotics **14**(1), 85.
DOI: 10.3390/antibiotics14010085

Sheikh A, Shrivastava V, Sharma E, Gaur N, Kumar S, Mittal S. 2025. Global status of micro/nano-plastic pollution and its effect on climate change. In Societal and Environmental Ramifications of Plastic Pollution (pp. 1–26). IGI Global.
DOI: 10.4018/979-8-3693-9163-1.ch001

Shi Q, Yuan Y, Zhou Y, Yuan Y, Liu L, Liu X, Li F, Leng C, Wang H. 2023. Pharmaceutical and personal care products (PPCPs) degradation and microbial characteristics of low-temperature operation combined with constructed wetlands. Chemosphere **341**, 140039.
DOI: 10.1016/j.chemosphere.2023.140039

Song Z, Wu H, Fang X, Feng X, Zhou L. 2024. The cardiovascular toxicity of polystyrene microplastics in rats: based on untargeted metabolomics analysis. Frontiers in Pharmacology **15**, 1336369.
DOI: 10.3389/fphar.2024.1336369

Stapleton MJ, Ansari AJ, Hai FI. 2023. Antibiotic sorption onto microplastics in water: a critical review of the factors, mechanisms and implications. Water Research **233**, 119790.
DOI: 10.1016/j.watres.2023.119790

Subaramaniyam U, Allimuthu RS, Vappu S, Ramalingam D, Balan R, Paital B, Panda N, Rath PK, Ramalingam N, Sahoo DK. 2023. Effects of microplastics, pesticides and nano-materials on fish health, oxidative stress and antioxidant defense mechanism. Frontiers in Physiology **14**, 1217666.
DOI: 10.3389/fphys.2023.1217666

Sulaiman RNR, Bakar AA, Ngadi N, Kahar INS, Nordin AH, Ikram M, Nabgan W. 2023. Microplastics in Malaysia's aquatic environment: current overview and future perspectives. Global Challenges **7**(8), 2300047.
DOI: 10.1002/gch2.202300047

Sun Q, **Liu L**, **Gong Y**, **Liu P.** 2024. Adsorption behavior and interaction mechanism of microplastics with typical hydrophilic pharmaceuticals and personal care products. Environmental Research **244**, 117897. DOI: 10.1016/j.envres.2023.117897

Talukdar A, **Kundu P**, **Bhattacharya S**, **Dutta N.** 2024. Microplastic contamination in wastewater: sources, distribution, detection and remediation through physical and chemical-biological methods. Science of The Total Environment, 170254.
DOI: 10.1016/j.scitotenv.2024.170254

Tang KHD. 2024. Microplastics and antibiotics in aquatic environments: a review of their interactions and ecotoxicological implications. Tropical Aquatic and Soil Pollution **4**(1), 60–78. DOI: 10.53623/tasp.v4i1.446

Titoy I, **Semerád J**, **Boháčková J**, **Beneš H**, **Cajthaml T.** 2024. Microplastics meet micropollutants in a central European river stream: adsorption of pollutants to microplastics under environmentally relevant conditions. Environmental Pollution **360**, 124616. DOI: 10.1016/j.envpol.2024.124616

Tong F, **Liu D**, **Zhang Z**, **Chen W**, **Fan G**, **Gao Y**, **Gu X**, **Gu C.** 2023. Heavy metal-mediated adsorption of antibiotic tetracycline and ciprofloxacin on two microplastics: insights into the role of complexation. Environmental Research **216**, 114716.
DOI: 10.1016/j.envres.2022.114716

Tumwesigye E, **Nnadozie CF**, **Akamagwuna FC**, **Noundou XS**, **Nyakairu GW**, **Odume ON.** 2023. Microplastics as vectors of chemical contaminants and biological agents in freshwater ecosystems: current knowledge status and future perspectives. Environmental Pollution **330**, 121829.

Wang K, **Guo C**, **Li J**, **Wang K**, **Liang S**, **Wang W**, **Wang J.** 2024. A critical review of the adsorption-desorption characteristics of antibiotics on microplastics and their combined toxic effects. Environmental Technology & Innovation, 103729.
DOI: 10.1016/j.eti.2024.103729

Wang Y, **Wang X**, **Li Y**, **Liu Y**, **Sun Y**, **Xia S**, **Zhao J.** 2021. Effects of coexistence of tetracycline, copper and microplastics on the fate of antibiotic resistance genes in manured soil. Science of the Total Environment **790**, 148087.
DOI: 10.1016/j.scitotenv.2021.148087

Wang YF, **Liu YJ**, **Fu YM**, **Xu JY**, **Zhang TL**, **Cui HL**, **Qiao M**, **Rillig MC**, **Zhu YG**, **Zhu D.** 2024. Microplastic diversity increases the abundance of antibiotic resistance genes in soil. Nature Communications **15**(1), 9788.
DOI: 10.1038/s41467-024-54237-7

Witczak A, **Przedpełska L**, **Pokorska-Niewiada K**, **Cybulski J.** 2024. Microplastics as a threat to aquatic ecosystems and human health. Toxics **12**(8), 571.
DOI: 10.3390/toxics12080571

Wojnowska-Baryła I, **Bernat K**, **Zaborowska M.** 2022. Plastic waste degradation in landfill conditions: the problem with microplastics, and their direct and indirect environmental effects. International Journal of Environmental Research and Public Health **19**(20), 13223.
DOI: 10.3390/ijerph192013223

Wu Q, **Wang X**, **Li HY**, **Huang DQ**, **Huang BC**, **Jin RC**, **Fan NS.** 2023. Perturbation and mechanism of non-antibiotic drug in regulating resistome and metabolome of anammox consortia: an overlooked and underrated cause of multiresistance. Chemical Engineering Journal **475**, 146325.
DOI: 10.1016/j.cej.2023.146325

Wu RT, **Chen JY**, **Liu S**, **Niu SH**, **Liao XD**, **Xing SC.** 2022. Cyclic AMP and biofilms reveal the synergistic proliferation strategy of Pseudomonas aeruginosa and Escherichia coli under the costimulation of high concentrations of microplastics and enrofloxacin. Science of the Total Environment **838**, 156470.
DOI: 10.1016/j.scitotenv.2022.156470

Xu S. 2024. Environmental legislation analysis improvement approach of global marine plastic pollution from the perspective of holistic system view. Frontiers in Marine Science **11**, 1481635.

Yang W, **Zhang H**, **Yang S**, **Xiao Y**, **Ye K**, **He R**, **Liu Y**, **Hu Z**, **Guo W**, **Zhang Q**, **Qu H**, **Mao Y.** 2024. Combined effects of microplastics and pharmaceutical and personal care products on algae: a critical review. Environmental Pollution, 124478. DOI: 10.1016/j.envpol.2024.124478

Yao J, **Li H**, **Yang HY.** 2023. Predicting adsorption capacity of pharmaceuticals and personal care products on long-term aged microplastics using machine learning. Journal of Hazardous Materials **458**, 131963. DOI: 10.1016/j.jhazmat.2023.131963

Yarahmadi A, **Heidari S**, **Sepahvand P**, **Afkhami H**, **Kheradjoo H.** 2024. Microplastics and environmental effects: investigating the effects of microplastics on aquatic habitats and their impact on human health. Frontiers in Public Health **12**, 1411389. DOI: 10.3389/fpubh.2024.1411389

Yu F, **Qin Q**, **Zhang X**, **Ma J.** 2024. Characteristics and adsorption behavior of typical microplastics in long-term accelerated weathering simulation. Environmental Science: Processes & Impacts **26**(5), 882–890. DOI: 10.1039/d4em00062e

Yu H, **Zhang Y**, **Tan W**, **Zhang Z.** 2022. Microplastics as an emerging environmental pollutant in agricultural soils: effects on ecosystems and human health. Frontiers in Environmental Science **10**, 855292. DOI: 10.3389/fenvs.2022.855292

Zahmatkesh Anbarani M, **Najafpoor A**, **Barikbin B**, **Bonyadi Z.** 2023. Adsorption of tetracycline on polyvinyl chloride microplastics in aqueous environments. Scientific Reports **13**, 17989. DOI: 10.1038/s41598-023-44288-z

Zhang H, **Shen N**, **Li Y**, **Hu C**, **Yuan P.** 2023. Source, transport, and toxicity of emerging contaminants in aquatic environments: a review on recent studies. Environmental Science and Pollution Research **30**(58), 121420–121437. DOI: 10.1007/s11356-023-30869-y

Zhang L, **Wang D**, **Yuan J**, **Chen J**, **Ding T**, **Zhu T**, **Li J.** 2024. Ecotoxicological impact of naproxen on Eisenia fetida: unraveling soil contamination risks and the modulating role of microplastics. Science of the Total Environment **928**, 172267. DOI: 10.1016/j.scitotenv.2024.172267

Zhang S, **Liu X**, **Qiu P**, **Chen B**, **Xu C**, **Dong W**, **Liu T.** 2022. Microplastics can selectively enrich intracellular and extracellular antibiotic resistant genes and shape different microbial communities in aquatic systems. Science of the Total Environment **822**, 153488. DOI: 10.1016/j.scitotenv.2022.153488

Zhang X, **Zhang Y**, **Li D**, **Wang J**, **Ding Y**, **Wang Y**, **Feng L**, **Hu Y.** 2024. Aging properties of polyethylene and polylactic acid microplastics and their adsorption behavior of Cd (II) and Cr (VI) in aquatic environments. Chemosphere **363**, 142833. DOI: 10.1016/j.chemosphere.2024.142833

Zhang Y, **Chen Z**, **Shi Y**, **Ma Q**, **Mao H**, **Li Y**, **Wang H**, **Zhang Y.** 2023. Revealing the sorption mechanisms of carbamazepine on pristine and aged microplastics with extended DLVO theory. Science of The Total Environment **874**, 162480. DOI: 10.1016/j.scitotenv.2023.162480

Zhao K, **Li C**, **Li F.** 2024. Research progress on the origin, fate, impacts and harm of microplastics and antibiotic resistance genes in wastewater treatment plants. Scientific Reports **14**(1), 9719. DOI: 10.1038/s41598-024-60458-z

Zhao M, **Huang L**, **Arulmani SRB**, **Yan J**, **Wu L**, **Wu T**, **Zhang H**, **Xiao T.** 2022. Adsorption of different pollutants by using microplastic with different influencing factors and mechanisms in wastewater: a review. Nanomaterials **12**(13), 2256. DOI: 10.3390/nano12132256

Zheng H, **Chen Q**, **Chen Z.** 2024. Carbon-based adsorbents for micro/nano-plastics removal: current advances and perspectives. Water Emerging Contaminants & Nanoplastics **3**(2). DOI: 10.20517/wecn.2023.74

Zheng Y, **Xu S**, **Liu J**, **Liu Z.** 2024. The effects of micro-and nanoplastic on the central nervous system: a new threat to humanity? Toxicology, 153799. DOI: 10.1016/j.tox.2024.153799

Zheng Z, **Huang Y**, **Liu L**, **Wang L**, **Tang J.** 2023. Interaction between microplastic biofilm formation and antibiotics: effect of microplastic biofilm and its driving mechanisms on antibiotic resistance gene. Journal of Hazardous Materials, 132099. DOI: 10.1016/j.jhazmat.2023.132099

Zhou L, **Masset T**, **Breider F.** 2024. Adsorption of copper by naturally and artificially aged polystyrene microplastics and subsequent release in simulated gastrointestinal fluid. Environmental Science: Processes & Impacts **26**(2), 411–420. DOI: 10.1039/d3em00354j

Zhou R, **Lu G**, **Yan Z**, **Jiang R**, **Bao X**, **Lu P.** 2020. A review of the influences of microplastics on toxicity and transgenerational effects of pharmaceutical and personal care products in aquatic environment. Science of the Total Environment **732**, 139222. DOI: 10.1016/j.scitotenv.2020.139222

Zhu X, **Luo T**, **Wang D**, **Zhao Y**, **Jin Y**, **Yang G.** 2023. The occurrence of typical psychotropic drugs in the aquatic environments and their potential toxicity to aquatic organisms—A review. Science of The Total Environment, 165732. DOI: 10.1016/j.scitotenv.2023.165732

Zhuang S, **Wang J.** 2023. Interaction between antibiotics and microplastics: recent advances and perspective. Science of The Total Environment, 165414. DOI: 10.1016/j.scitotenv.2023.165414