Transport, Fate, and Toxicity of Microplastic and Organic Co-Existing Contaminants in the Marine Environment

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Group 14 (Green Land)

Pejman Mokari (#202196513)

Sadegh Rajabi (#202292375)

MD Sakil Ahmed (#202196513)

Nahidul kabir Siddiki (#202291960)

Project Supervisor: Min Yang

Course Instructor: Dr. Baiyu Zhang

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Nomenclature

Antibiotics	ATs
Dichlorodiphenyltrichloroethane	DDT
Hexachlorobenzene	HCB
Microplastics	MPs
Nanoparticles	NPs
Organic Matter	OM
Per- and Polyfluoroalkyl Substances	PFASs
Polychlorinated biphenyls	PCBs
Polycyclic aromatic hydrocarbons	PAHs
Sea Surface Temperatures	SST

Abstract

One of the most important causes of ocean pollution is plastics waste entering the ocean. Microplastics (MPs) are plastic particles smaller than 5 mm, and they widely exist throughout the seawater column. MPs have attracted many concerns in the last decade. Due to their small size, MPs have the ability to spread in seas and oceans. The primary determinant of the release of MPs is the high level of surface absorption exhibited by these particles. What increases the toxicity of MPs pollution is their integration with persistent organic pollutants. MPs and their toxic effects gradually enter the food chain and endanger the health of animals and human societies. In this project, we summarized the formation, transport, and fate of the MP and co-existing organic contaminants, such as polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), antibiotics,.etc , the interaction between MPs and organic contaminants under different ocean conditions such as salinity, temperature, mixing energy, as well as suspended particles have been investigated In addition, the study on the effect of MPs ecological system on human health and marine organism such as zooplankton are demonstrated. The findings of this report may build up thefoundation for summarizing the interaction of MPs and organic contaminants.

1. Introduction

1.1. Background

1.1.1. Distribution of MPs

Over the past few decades, global plastic manufacturing and the accumulation of waste have witnessed a steady increase (Geyer et al., 2017; PlasticsEurope, 2018). This surge in plastic production has resulted in a pervasive problem known as plastic pollution, which is particularly prevalent in various environments, including oceans. Extensive research has highlighted the detrimental impact of plastic products on the environment. Plastic pollution has reached alarming levels due to the continuous increase in plastic manufacturing and inadequate disposal practices for plastic waste (Bank et al., 2021; Shen et al., 2021a). The fragmentation of larger plastic objects into smaller pieces has emerged as a significant concern, as the environmental and ecosystem effects of these plastic fragments vary depending on their size. Due to the limited availability of effective biodegradation methods, a significant portion of plastic waste is not properly managed and ends up in landfills or the natural environment. It is estimated that as of 2017, approximately 8.3 billion metric tons of raw plastics have been produced, and by 2050, it is projected that there will be around 12,000 tons of plastic waste in landfills or the natural environment (Geyer et al., 2017). The continuous production and slow degradation of plastics, particularly MPs, have led to their accumulation in the marine environment.

To categorize these minutes plastic fragments, the term MPs was coined, referring to plastic particles that result from the breakdown of larger plastic objects due to factors such as light, heat, and mechanical collision (Thompson et al., 2004). Although there is no clear consensus on the

exact size range, many studies define MPs as particles smaller than 5 mm, while even smaller plastic fragments are referred to as nano plastics (NPs). Alimi et al. (2018) define MPs and NPs as plastic fragments with diameters ranging from 100 nm to 5 mm and less than 100 nm, respectively. Polyethylene (PE), Polypropylene (PP), Polystyrene (PS), Polyvinyl chloride (PVC), Polyester, Polyurethane (PUR), Polyethylene Terephthalate (PET), Polyamide (PA), High-Density Polyethylene (HDPE), Ethylene Vinyl Acetate (EVA), Cellulose Acetate (CA), etc. are the main polymer types of MPs found in the marine environment. From 0.028 to 1.58 g/cm3 are the densities (Di Pippo et al., 2020). The origin of MPs can be classified into primary and secondary categories. Primary MPs refer to microscopic particles that are initially produced as part of plastic-containing products and subsequently enter the environment. These primary MPs arise from the release of fibers or microbeads found in textiles, pastes, cosmetics, paints, gels, and other consumer products. On the other hand, secondary MPs originate from the fragmentation of large plastic debris, which can include items like plastic bags, fishing nets, and beverage bottles (Ajith et al., 2020; Cole et al., 2011; Wang et al., 2021a). As a result, the sources of secondary MPs are diverse and contribute significantly to the overall accumulation of MPs. Notably, MPs account for a significant portion of plastic pollution, with approximately 92.4% of the 5.25 trillion particles found on the ocean's surface falling into this category (Eriksen et al., 2014).

1.1.2. Source of marine MPs

The sources of MPs entering the ocean primarily include coastal land and river inputs, atmospheric transport, and human activities (Andrady, 2011; Liu et al., 2019; Zhang et al., 2020). Coastal land and rivers are significant contributors to marine plastic waste, accounting for approximately 80% of the total plastic waste found in the ocean (Andrady, 2011). Rivers, in particular, play a crucial role in the transport of plastic waste, with an estimated 1.15 million to 2.41 million tones of plastic

entering the sea through rivers annually (Lebreton et al., 2017). The majority (98%) of primary MPs originate from terrestrial sources, while only a small proportion (2%) comes from marine activities (Peng et al., 2020). Secondary MPs, which result from the degradation of plastic fragments, are mainly sourced from river transport, as rivers tend to collect a significant amount of plastic waste due to their slow flow rate (Xu et al., 2020; Wang et al., 2022b). Furthermore, MPs present in terrestrial soils can also contaminate the aquatic environment through river systems (Hu et al., 2022). Therefore, implementing measures to control plastic input from land can have a substantial impact on reducing marine plastic pollution.

Atmospheric transport plays a crucial role in the distribution of MPs, with the potential for deposition into terrestrial or aquatic environments. This form of transport significantly affects the dynamics of plastic pollution, including the transfer between terrestrial and marine ecosystems (Zhang et al., 2020). Atmospheric MPs have been detected far from coastal areas, indicating their ability to travel long distances through the atmosphere. The transport of MPs through the atmosphere is influenced by atmospheric circulation and dynamics (Liu et al., 2019). It has been observed that almost all plastics carried by atmospheric transport are in the form of MPs (Ding et al., 2021; Liu et al., 2019). Furthermore, atmospheric transport is a potential pathway for MPs in polar environments (Gonzalez-Pleiter et al., 2020).

Fishing activities, aquaculture, shipping, and water operations also contribute to marine plastic waste (Tang et al., 2021). The fishing industry, for instance, has been identified as an important source of MP pollution in coastal areas, with previous studies suggesting that fishing activities account for approximately 18% of marine plastic debris (Andrady, 2011). Old fishing nets and ropes can generate a significant amount of plastic fibers and fragments, making them potential sources of MPs (Chen et al., 2018). Additionally, the growing mariculture industry, which utilizes

various plastic equipment such as fishing nets, buoyancy materials, and cages, can also contribute to local seawater contamination with MPs due to long-term photodegradation and mechanical friction (Chen et al., 2022).

The sources of MPs entering the water range from synthetic textiles to personal care products, Figure 1 shows the percentage of each MPs discharge to marine system. Research shows that synthetic textiles are the largest contributor, accounting for 35% of MPs in the water. Tires are another significant contributor, making up 28% of MPs, and city dust is responsible for 24%. Painting and marine coating contribute 7% and 4%, respectively, while personal care products account for 1.7%, and plastic pellets make up 0.3% of MPs (Boucher & Friot, 2017). As a result of MPs' buoyancy and light density, as well as the water's capacity to flow, which carries the majority of MPs elsewhere, freshwater ecosystems and places that have been contaminated by MPs have typically been neglected (Rochman Chelsea, 2018) .

1.1.3. MP transport and fate

The worldwide occurrence of MPs in the aquatic environment is caused by the widespread use of plastic products (Du et al., 2021). MPs can originate from a variety of places, such as urban runoff, limitless oceanic accumulations, and plastic debris along riverbanks and coastlines (Fiore et al., 2022). Different MP entry points into the aquatic environment include urban drains, road runoff, landfill leachate, agricultural areas, and wastewater treatment facilities (Priya et al., 2022). Numerous factors, including ocean currents, wind, and waves, have an impact on the movement of MPs in the marine environment (Du et al., 2021). Marine environment is a particularly significant pathway for MP transport, with approximately 80% of plastic debris entering the ocean originating from land-based sources, while the remainder is contributed by shipping and fishing

activities (Andrady, 2011; Khalid et al., 2021). Due to the influence of ocean currents, wind patterns, and sea ice dynamics, plastic particles can travel considerable distances (Yu et al., 2018; Alosairi et al., 2020; Peeken et al., 2018). As a result, buoyant MPs can be transported across vast ocean surfaces. Over time, natural degradation and the colonization of attached organisms enable MPs to undergo vertical movements. Consequently, MPs have been detected in diverse oceanic regions, including the Antarctic sea ice, Arctic ecosystems, and even the Mariana Trench (Kelly et al., 2020; Carlsson et al., 2021; Peng et al., 2018).

Marine and riverine animals ingest plastic particles smaller than 2 mm, while seabirds consume pieces of plastic measuring 5 mm or smaller (Moore, 2008; Wilcox et al., 2015). This phenomenon highlights the potential risks associated with plastic pollution in diverse habitats. The invention of plastic has undoubtedly facilitated numerous aspects of human life, with a wide range of plastic products being utilized in daily production and consumption (Wang et al., 2016; Wang et al., 2022b). However, the non-degradable nature of plastic has caused significant environmental harm, leading to various environmental issues and potential ecological risks that have gained increasing attention from scholars.

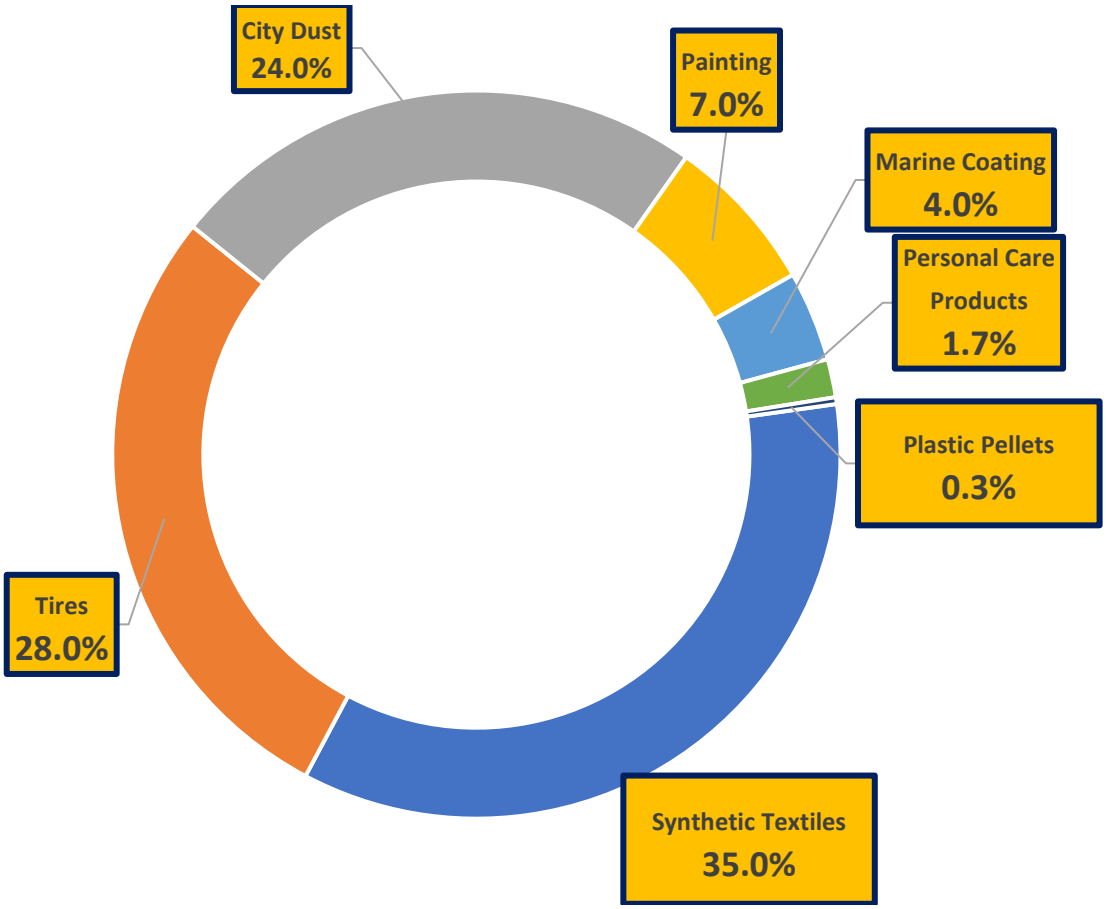

Figure 1. Ordinary consumer products are the source of most of the marine microplastics (Boucher & Friot, 2017).

In the marine environment, organic contaminants have a complex and varied range of sources. A number of non-point-source transport pathways, such as atmospheric deposition, runoff from the land, and ship discharge, allow organic contaminants to enter the world's oceans (Giam & Dou, 2013). Depending on their sources and physicochemical characteristics, organic contaminants in coastal environments are complex mixtures of different compounds (Bayona & Albaigés, 2006).

Organic pollutants like PCBs, organochlorine pesticides, and polybrominated diphenyl ethers have been found in the deep sea, according to several studies (Sanganyado et al., 2021). Chemically active substances that are released from industries are considered organic contaminants. These might migrate to reach marine water (Sharma & Negi, 2020). Due to their resistance, organic compounds known as persistent organic pollutants (POPs) are present in the marine environment everywhere (D'Agostino et al., 2020).

1.1.4. Source and distribution of organic contaminants

Industrial, agricultural, and other anthropogenic activities have introduced numerous pollutants, predominantly synthetic organic compounds, into the marine environment (Dachs and Me´janelle 2010). Also A class of organic compounds known as PAHs are created when fossil fuels, wood, and other organic materials burn insufficiently. They are frequently discovered in marine sediments from developed areas. Persistent organic pollutants are a subset of these compounds, raising concerns due to their toxicity, persistence, bioaccumulation tendency, and ability to undergo long-range atmospheric transport.

Traditionally, significant attention has been given to a few POPs families such as PCBs, organochlorine pesticides (OCPs) like Dichlorodiphenyltrichloroethane (DDT) and hexachlorobenzene (HCB), as well as dioxins and furans (PCDD/Fs) and PAHs resulting from industrial processes or combustion (Dachs & Me´janelle, 2010). However, these families represent only a fraction of the total known pollutants in the marine environment, and likely of the overall potential pollutants present (Muir & Howard, 2006). Nonetheless, these few families of POPs have

been detected worldwide in abiotic and biotic matrices (Gioia et al., 2006, 2008a; Gilman et al., 1997; Jaward et al., 2004).

- Emerging Challenges and New Chemicals

Chemicals with similar or different physical-chemical properties, such as polybrominated diphenyl ethers (PBDEs) and fluorinated compounds (PFs), are currently being manufactured and widely used, potentially entering the environment and posing new challenges for environmental management (Dachs & Me´janelle, 2010). The cycling of these chemicals in the environment is highly complex, controlled by air-surface exchange and interactions with the carbon cycle, particularly organic and soot carbon fractions. Due to their hydrophobic nature, some of these chemicals have the potential to accumulate in ecosystems' trophic levels, even in distant regions. The number of known organic pollutants in marine waters has significantly increased in recent years thanks to analytical advancements (Dachs & Me´janelle, 2010).

- Complexity and Ionic Character of Chemical Behavior

The source and distribution of organic contaminants are significantly influenced by the complexity and ionic nature of chemical behavior. Solubility and Hydrophobicity, Common organic contaminants have a wide range of solubilities that can be affected by a number of variables, including temperature, salinity, hydrophobicity, and dissolved organic matter (National Research Council, 1994). While knowledge primarily focuses on a few chemical families (e.g., PCBs, HCHs, DDT, PAHs), these families should be considered as markers or "surrogates" for other pollutants with similar physical-chemical properties in marine waters (Dachs & Me´janelle, 2010). Furthermore, chemicals with different physical-chemical properties (e.g., greater water solubility, low volatility) can reach coastal and open oceans via rivers and exhibit different environmental

behaviors due to their ionic character. Some emerging compounds have been suggested to act as passive tracers in water, distinct from legacy POPs like PCBs or HCHs (Yamashita et al., 2008).

- The Anthropogenic Organic Chemosphere in the Marine Environment

The marine environment contains a significant number of anthropogenic organic substances at trace levels (Crutzen & Stoermer, 2000). The term "Anthropocene" was introduced to highlight humans as a major geophysical force on Earth, with two distinct stages: the industrial era (1800-1945) and the great acceleration (1945-present) (Steffen et al., 2007). The production and use of synthetic organic substances have substantially increased during the second half of the twentieth century. Chemical pollution, including hydrocarbons like PAHs and alkanes, likely began to rise during the industrial era due to fossil fuel usage.

1.1.5. Toxicity of MP and organic co-existing contaminants

MPs pose a risk to both protected species and species important for human consumption, such as oysters, prawns, mussels, and fish (Walkinshaw et al., 2020). MPs can move up the aquatic food chain from the lowest trophic level (phytoplankton), making their way to higher trophic levels and accumulating in the tissues of organisms (Walkinshaw et al., 2020) .Other contaminants, such as organic pollutants, may bioaccumulate in the tissues of these organisms as a result of this accumulation (Kinigopoulou et al., 2022). The effects of organic contaminants on marine ecosystems and human health can be made more severe by the presence of MPs in the marine environment (Cverenkárová et al., 2021). Plastic waste of any size increases the risk of harmful substances escaping into the environment and contaminating the food supply in addition to the risks associated with direct consumption (Cverenkárová et al., 2021). Marine organisms may be at risk from ingesting microplastics with pollutants attached, especially if they enter the food chain

(Cverenkárová et al., 2021). Research into indicator species from the marine environment can help determine the degree of pollution in seafood and other organisms meant for human consumption (Cverenkárová et al., 2021). Since they are consumed whole and can be a significant source of microplastics, mussels, and mollusks are good indicators. Benthic fish may indicate sediment contamination (Cverenkárová et al., 2021). Along with the dangers of direct consumption, plastic waste of any size raises the possibility of hazardous compounds escaping into the environment and contaminating the food supply (Engler, 2012; Koelmans et al., 2014).

Studies have found that MPs and co-existing organic contaminants may be toxic to marine species, while rare studies summarized the toxic effects of co-contaminants on marine species and human health (Ning et al., 2022; Sun et al., 2018). Due to their potential negative impacts on marine ecosystems and human health, their co-existing contaminants in the marine environment have become a major global concern. The majority of research on the effects of MPs on marine organisms has been done in labs and on the ground (Rehse et al., 2016)., such as zooplankton, corals, fish, fur seals, and whales that consumed MPs from the maritime environment at various trophic levels. Numerous studies have also demonstrated that marine creatures, such as mussels, swallowed the MPs in laboratory conditions (Farrell & Nelson, 2013), freshwater bivalves, krills, pelagic species, amphipods, and fish. The transfer of MPs from zooplankton to mysid shrimps and from mussels to crabs has also been shown in studies conducted in a lab setting (Setala et al., 2014). Aquatic species such as vertebrates, invertebrates, and zooplanktonic organisms (Covernton et al., 2019; Kokalj et al., 2018) can quickly ingest MPs via water and food because of their small size (Zhao et al., 2016; Mazurais et al., 2015; Jabeen et al., 2017). MPs can enter the Daphnia body by feeding or water uptake. The MPs attached to the surface of the algae can serve as food for the daphnia. As a result, MPs are frequently concentrated in the intestine, which may have an

additional impact on D. magna development (Gross et al., 2016), eating, motility, and reproduction (Besseling et al., 2014; Ogonowski et al., 2016; Rehse et al., 2016). (add some information about the toxicity of MP and organic co-contaminants, some examples.)

When MPs attach to marine organisms such as zooplankton, they threaten biological health through oxidative stress, endocrine disruption, nerve and immune injury, and other mechanisms. Moreover, when MPs exist in the marine environment, under certain ocean conditions, the interaction between MPs and persistent organic contaminates has uncertain impacts on organisms, mainly detrimental. Many scholars have scrutinized the specific parameters of MPs. However, there is a lack of comprehensive review and summarization of all collected data. Therefore, in this study, we reviewed the interaction between MP and co-existing organic contaminants such as PAHs, PCBs, antibiotics, nanoparticles (NPs), and pesticides under various ocean conditions and related toxic effects. Ocean conditions include seawater salinity, temperature, mixing energy (i.e., excite internal/external waves and turbulent mixing), and suspended particles. In addition, the studies regarding the effect of MPs toxicity on marine organisms such as zooplankton were summarized. Findings from this report will contribute to understanding the MPs' interaction with organic contaminants, as well as the ocean conditions effects on their sorption of them. Moreover, the toxicity of MPs and organic contaminants was briefly explained.

1.1.6. MPs and co-existing contaminants

Various types of organic contaminants, such as pesticides, hydrocarbons, plasticizers, detergents, oils, and pharmaceuticals, have been discovered in environmental ecosystems, particularly in bodies of water (Kinigopoulou et al., 2022). These organic pollutants can pose additional

ecological hazards and harmful consequences to living organisms due to their resistance to environmental breakdown and their ability to accumulate easily in food chains (Volkman, 2006).

Some of these pollutants, which lack hydrophilic functional groups and may contain halogen substitutions like chlorine, are highly resistant to breakdown in the environment. These organic pollutants can accumulate easily in food chains and pose additional ecological hazards and harmful consequences to living organisms.

Pollutants come in various complex forms, and they are generally categorized into organic pollutants and inorganic pollutants. However, there are some pollutants that do not fit into either category, and they are classified as an additional type of pollutant. Organic pollutants primarily consist of carbon chains and carbon rings, including acids like acetic acid and formic acid, as well as benzene rings such as phenanthrene, nitrobenzene, and naphthalene. In contrast, inorganic pollutants are mainly salts, and they often transform into ion form in water due to ionization, hydrolysis, and other effects. Metal ions are the most common pollutants in this category, but some metals like mercury can maintain their original form due to their stable physical and chemical properties. Some fibers such as fiber carbon and fiber metal materials are also classified as inorganic pollutants. Some pollutants are mixtures, such as oils and medicines, which can decompose and recombine into new substances under certain temperatures. These composite pollutants are classified separately as their content and composition cannot be clearly quantified (Gao, X, 2021).

There are various kinds of pollutants, and as a result, many different types of MPs adsorbents are used for sewage treatment. A literature review on the adsorption of plastics on different pollutants has found that multiple factors affect the adsorption of plastics on pollutants. Figure 2 illustrates

the adsorption of MPs on contaminants and the various factors that influence it (Yu, F et al, 2019). The adsorption outcomes differ depending on the influencing factors. For instance, MPs, heavy metals, and pollutants may form complexes, exhibiting different properties due to atomic valence, atomic size, surface texture, and functional groups. Additionally, different adsorbents have varying adsorption effects. Biochar, for instance, can be an excellent adsorbent for treating high-concentration NH^{4+} wastewater, and the interaction between biochar and PE can alter the surface properties of the adsorbent. Furthermore, the same influencing factors, such as pH, temperature, and functional groups, show different phenomena in different adsorption experiments (Yu, F et al, 2019).

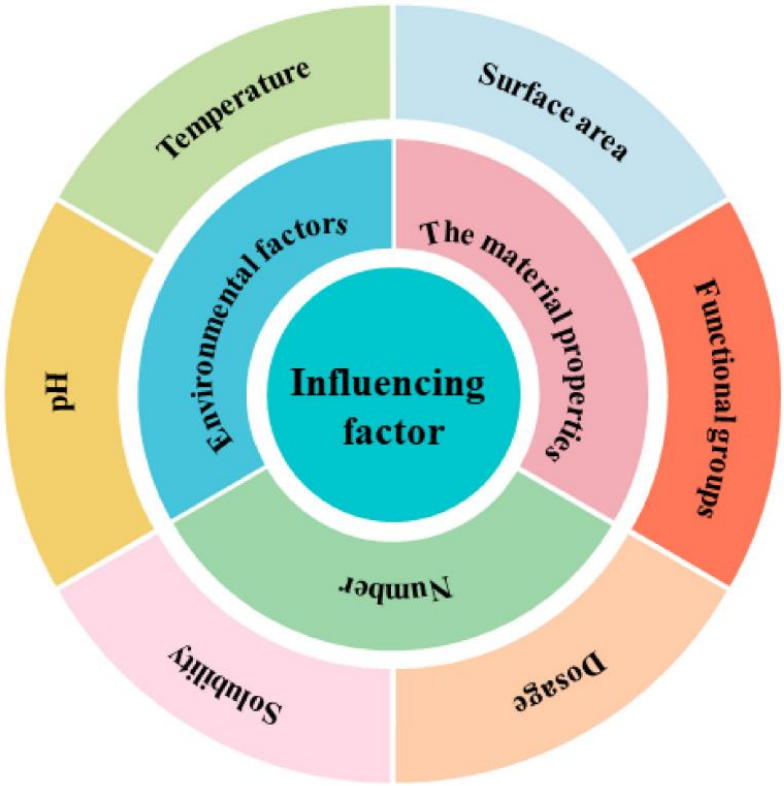

Figure 2. Various factors influence the adsorption of pollutants by MPs (Yu, F et al, 2019).

However, in this study, we analyzed the number of research publications on MPs, shown in Figure 3. It is clear that the research number tremendously increased just a few years ago. Our data collected come from impactful journals such as *Science of the Total Environment*, *Marine Pollution Bulletin*, *Environmental Pollution*, and the most cited articles. Figure 3 demonstrates that only in the beginning of 2023, over 800 research were published, indicating the importance of MPs studies. However, there is a lack of available information on the co-occurrence of organic pollutants and MPs. POPs are toxic substances discharged and released into the territorial and marine environment via anthropogenic activities. Obviously, POPs could have irreversible adverse effects on ecosystems, people, and wildlife. PAHs are a class of organic pollutants that are commonly associated with the combustion of fossil fuels, industrial processes, and various forms of pollution. These compounds are known to be persistent, bioaccumulative, and toxic to both aquatic and terrestrial organisms. In the context of MPs, PAHs can be adsorbed onto the surface of plastic particles, potentially exacerbating the ecological risks associated with MPs. The co-occurrence of PAHs and MPs in the environment warrants further investigation to better understand the potential interactions and impacts of these pollutants on ecosystems and human health.. Understanding the interaction of MPs and organic pollutants is essential as the transport, fate, and toxicity of their co-existing contaminants may be changed tremendously compared with MP and organic contaminants themselves.

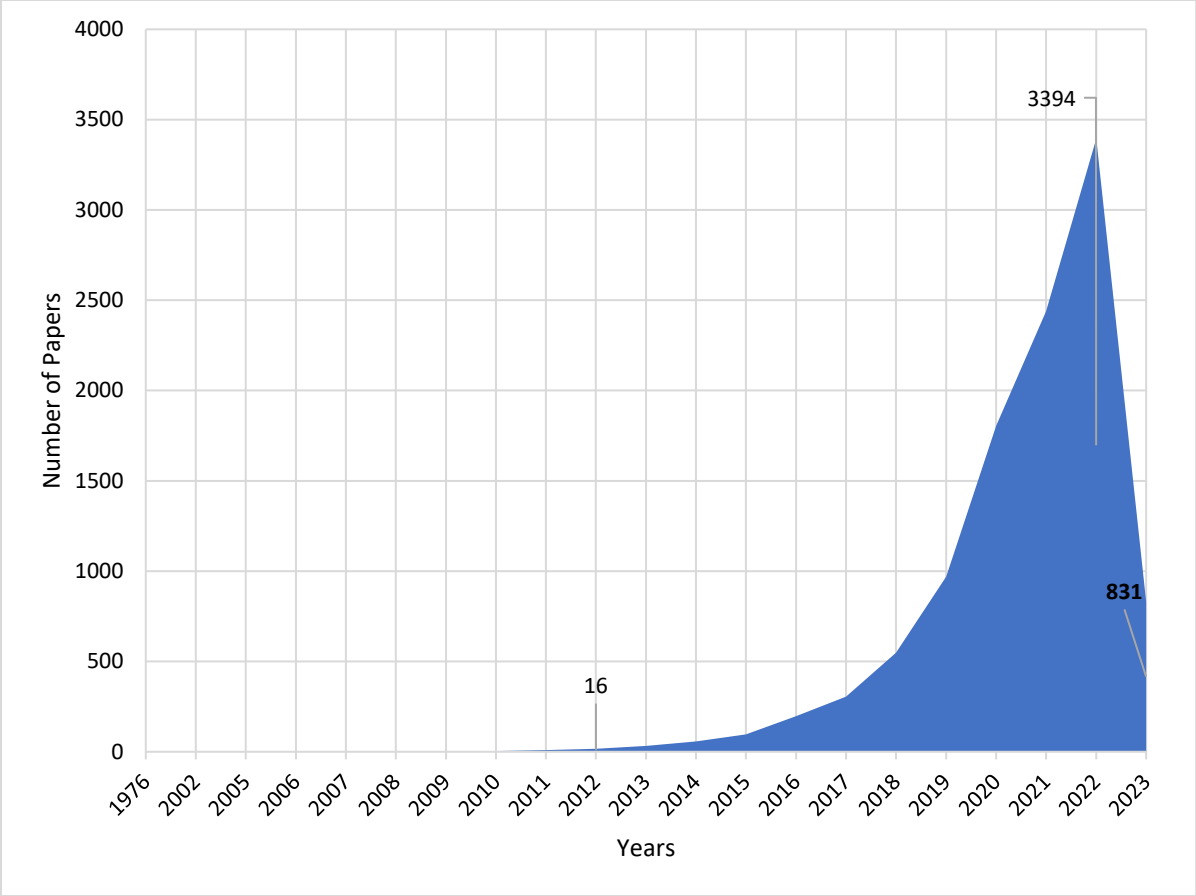

Figure 3. Number of Publications on the topic of microplastics

In aquatic ecosystems, MPs frequently bind to contaminants such as PAHs, organochlorine insecticides, and other persistent organic compounds (Wang et al., 2017). The deterioration of the material over time is well recognized to be the cause of variations in the surface roughness of plastics. Organic contaminants that are hydrophobic or hydrophilic can be carried by MPs because of their rough surface, which also increases their surface area. Due to the large surface roughness and specific surface area, MPs have a high sorption capacity for hydrophobic pollutants such as PCBs, PAHs, and other compounds with benzene rings are the primary contaminants (X. Liu et al.,2019; Rios et al., 2007). In addition, studies found that hydrophobic organic pollutants

frequently interacted with the hydrophobicity of virgin plastic debris, such as PS, and some hydrophilic organic pollutants, such as PAH, have a high absorption ability on MPs like PE (Yu et al., 2019). Furthermore, MPs were found to adsorb hydrophilic antibiotics like sulfadiazine (SDZ), amoxicillin (AMX), tetracycline (TC), ciprofloxacin hydrochloride (CIP HCl), and trimethoprim (TMP), with distribution coefficient (Kd) values ranging from 7.36 to 756 L/kg (Li et al., 2018; Shen et al., 2018).

1.2. Statement of problems

Due to potential synergistic effects and intricate interactions that may occur in the marine environment, it is crucial to investigate co-existing contaminants, particularly MPs and organic pollutants. Despite the fact that the effects of MPs and organic pollutants have alone been the subject of substantial research, their combined effects are still poorly summarized. To fill this information vacuum and shed light on the interaction between MPs and co-existing organic contaminants in the marine environment in different conditions such as salinity and temperature, conducting a literature review to summarize the co-existence of these contaminants is important.

Determining the ecological and health problems connected with the presence of MPs in the marine environment also requires research into the toxicity of co-existing organic pollutants. Previous research has demonstrated that both MPs and organic pollutants have the potential to negatively impact a wide range of organisms, from phytoplankton to higher trophic levels. However, limited information is on the toxicity of the MPs and organic co-contaminants and it is necessary to summarize all these information to provide guidance for further research on the environmental risks of these co-contaminants.

In addition, determining the risks co-existing pollutants pose to human health requires an understanding of their potential transit up the food chain. MPs and organic contaminants are exposed to marine creatures, including fish and shellfish, both directly and indirectly through the consumption of contaminated prey. Understanding the bioaccumulation and biomagnification processes of these pollutants by synthesising the current literature will help in the evaluation of possible human exposure and related health impacts.

A comprehensive understanding of the MP and organic co-existing contaminants under various conditions in the marine environment will help with the decision-making and the creation of successful mitigation strategies.

1.3. Objectives

The objectives of this literature review are to comprehensively examine the interactions between MPs and co-existing organic contaminants, including PAHs, PCBs, antibiotics (ATs), pesticides, Per - and polyfluoroalkyl substances (PFAs). Additionally, the review aims to analyze the impacts of ocean conditions, such as salinity, temperature, mixing energy, suspended particles, pH, and MP weathering, on the interactions between MPs and organic co-existing contaminants. Furthermore, the toxicity of these co-existing contaminants to various organisms, including phytoplankton, zooplankton, and high trophic-level species, will be evaluated to understand the ecological implications. The review will also assess the potential human health risks associated with these co-existing contaminants in the marine environment. The findings will be summarized, and recommendations will be provided for future research, risk assessment, and the development of effective mitigation strategies. The development of a consistent nomenclature and the inclusion of relevant citations and references will support the review's findings and recommendations. (The

findings will provide valuable insights for future research directions and inform the development of effective measures to mitigate the adverse impacts of MPs and organic co-contaminants, safeguarding marine ecosystems and promoting human well-being.

2. Interactions between MPs and organic co-existing contaminants

The interaction between MPs and organic contaminant is complicated and hence need a full investigation between both components. Therefore, there is no direct relation between them. For this purpose, before any further analysis, we need to make a sample from interested marine points and then detect the properties of MPs and organic compounds. Figure 4 displays some of the most important properties to be analyzed.

For instance, the density of MPs can play a significant role in the interaction of them. If the density of MPs is low such as PP (0.895 and 0.92 g/cm^3), it could be buoyant on the surface of the water column and the interaction with organic contaminants is affected. Based on our literature review, we figured out that the chief and direct factor of pollutant sorption by MPs is chemical interaction. These factors are categorized in Figure 5.

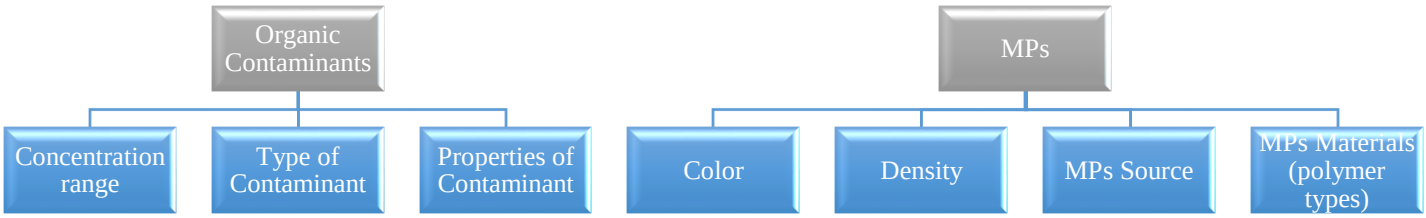

Figure 4. Some physicochemical properties for the interaction of MPs and contaminant analysis

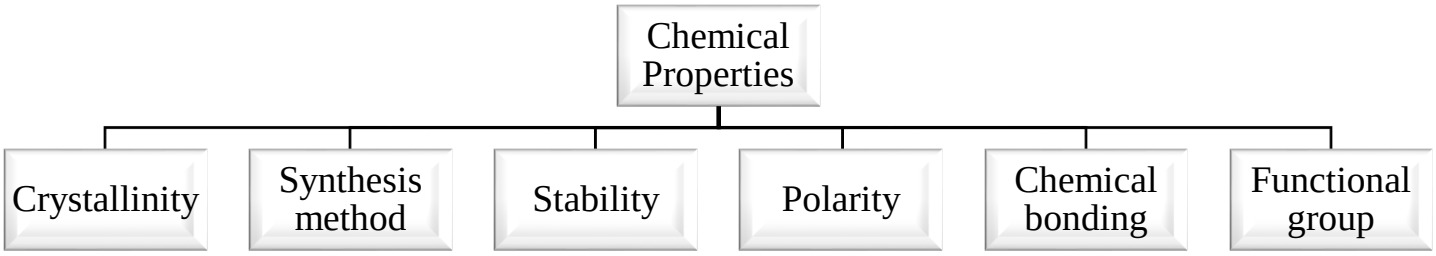

Figure 5. Chemical properties to be analyzed for MPs and contaminant interaction.

2.1. Polycyclic aromatic hydrocarbons (PAHs) and MPs

The past few years have illustrated many experimental studies dealing with the interaction of MPs and PAHs. MPs and PAHs are globally detected in the marine ecosystem and proved to have adverse impacts on marine species. PAHs are a group of hydrophobic chemicals with two or more aromatic rings and are almost generated from the combustion of organic materials such as coal and oil, as well as petroleum pollution such as oil spills and tank leakage (Tang et al., 2018). PAHs can be generated by industrial activities, coal combustion, biomass combustion as depicted in Figure 6.

Figure 6. PAHs generation ways (kim and et al, 2013)

In particular, large specific surface areas of MPs can absorb high concentrations of other PAHs pollutants, making it smoother to move deeply of these pollutants into marine organisms. Up to date, the understanding of this interaction has been almost proven by studies investigating the cooperation impacts of MPs and a few specific PAHs, such as Benzo a pyrene, phenanthrene,

pyrene, fluoranthene, and anthracene on some marine organisms (Tan, X et al., 2019). A case study proved that the sorption mechanism and capacity of PAHs are dependent upon MP polymer type and size, as well as the sorption capacity of PAHs to PE and PS MP increases with seawater temperature (Sørensen et al, 2020). Another study investigated the sorption of PAHs by MPs under static conditions. After 24 h of adsorption 1255 μg/g of carcinogenic PAHs was adsorbed onto MPs (polyester fibers) (Wiśniowska et al, 2022). However, investigating PAH pollution scenarios on MPs with dozens of different PAH compounds present simultaneously needs more verification and research.

PAH adsorption on MP surface could be determined by MP type (e.g. polymer structure), PAHs properties (e.g. molecular weight and hydrophobicity), and marine environmental conditions (e.g. weathering, salinity, temperature). According to a study by (Sørensen et al. 2020), PE and PS on MPs have a higher capacity for sorbing hydrophobic organic chemicals compared to other MP materials. The surface properties of MPs, such as their shape and size, play a role in determining the surface-to-volume ratio, which in turn affects the equilibrium time, as well as the adsorption and desorption rates of hydrophobic organic chemicals (Teuten et al., 2009). In addition, Wang et al. (2019) conducted research on the sorption of phenanthrene and nitrobenzene using PE-MPs of different sizes and found that the partition coefficient (Kd) of pollutants increases with decreasing particle size, specifically with micron-sized and submicron-sized PE-MPs. However, when MPs are reduced to the nanometer range, their ability to absorb pollutants diminishes due to nanoparticle aggregation.

Van et al., (2012) discovered that the concentration of PAHs in MP foams is higher compared to MP fragments and films. Additionally, Tan et al., (2019) demonstrated that extracellular polymeric substances (EPS) have a higher adsorption capacity for PAHs compared to PE and PP, possibly

due to EPS having a larger surface area per unit weight compared to PE and PP. The properties of PAHs play a significant role in the sorption process onto MPs. PAHs with higher molecular weight and hydrophobicity take longer to reach equilibrium, indicating greater adsorption onto MPs. The partition coefficient of PAHs also affects the rate of desorption, with lower partition coefficients corresponding to faster desorption rates. Additionally, weathering of MPs can lead to their embrittlement and fragmentation, increasing surface area and enhancing sorption capacity (Hartmann et al., 2017).

Ultraviolet light exposure can introduce oxygen-containing functional groups on the surface of MPs, allowing them to form hydrogen bonds with surrounding water molecules. This interaction may reduce the accessibility of sorption sites on MPs (Teuten et al., 2009). Furthermore, the formation of three-dimensional water clusters can block nearby sorption sites, thereby reducing the adsorption coefficient of MPs for hydrophobic organic compounds (Hüffer et al., 2018). Overall, understanding the factors influencing PAHs adsorption onto MPs is challenging and complex.

Studies have shown a wide range of PAHs concentrations in MPs in the marine environment, varying between 10^1 and 10^5. This disparity can be attributed to several factors (Tan et al., 2019).:

- Regional variations in the degree of PAH pollution, leading to different concentrations of PAHs in MPs;
- Variations in the physical and chemical properties of MPs, such as size, shape, and polymer type, which can affect their ability to adsorb PAHs; and
- The extent of environmental weathering and aging of MPs, which alters their physical and chemical properties and affects their sorption capacity for PAHs.

2.2. Polychlorinated biphenyls (PCBs) and MPs

PCBs are considered inheritance contaminants and have been under research widely. From the 1950s to the 1960s, the application of PCBs in the industry demonstrated a high value. They are one of the most industrial products and chemicals. Environmental protection agency (EPA) marks the PCBs belonging to human-made organic chemicals for families called chlorinated hydrocarbons. PCBs are accused of being the reason for carcinogens and exert various toxicological impacts, such as skin injuries, reproductive abnormalities, and chronic diseases (Kennish, 1997).

Concentrations of PCBs in floating MPs in open body water have been reported in several case studies (Chen et al., 2018). For instance, (B.G. Yeo et al., 2018) focused on the presence of PCBs in MPs and zooplankton obtained from surface water samples at 27 different locations in the Pacific Ocean and along the coast of Japan. Even in smaller MP particles measuring 0.315–1 mm, PCBs were found. The concentrations of PCBs ranged from 0.04 to 124 ng/g, with higher levels observed in urban bay areas like Tokyo Bay. Moderate to high concentrations of PCBs were sporadically detected in both urban-offshore and rural-offshore locations, primarily consisting of more highly brominated variants. By establishing a threshold, it was determined that the ratio of MP abundance to zooplankton abundance needed to exceed 0.6 for PCBs to indicate that exposure from MPs was greater than that from zooplankton. Polypropylene homo-polymer was found to have the highest adsorption levels of PCB congeners. To test the uptake of PCBs through MP ingestion, the researchers used the herbivorous rabbitfish, Siganus rivulatus, in an outdoor mesocosm located in the eastern Mediterranean Sea. They mixed Polypropylene homo-polymer particles (0.3–5.0 mm) pre-saturated with 11 PCB congeners, at two concentrations (500 ng/g and 5000 ng/g), with dough and fed it to the fish. The researchers found that PCBs were present in the

fish muscle tissues after two weeks, but not in the liver. These findings suggest that the ingestion of contaminated MPs by rabbitfish may have long-term negative effects on their health, as well as on those who consume them regularly, such as rabbitfish predators and humans (van der Hal et al, 2020). PCB contaminations are mainly found in rivers, harbors, industrialized and urban surrounding bays, and body water because of its discharge, such as New Bedford Harbor in Massachusetts in a high concentration, where it can be loaded by MPs readily. While PCBs contaminations from moderate to high concentrations were almost approved in offshore locations (Yeo et al., 2019). It has been reported that the affluence of PCBs with lower chlorinated recommends that chemical additives in MPs is an of great importance and plays a vital role as a pollutant source, as well as transportation of chemical. Furthermore, another research showed that the exposure of PCB daphnids (a genus of small planktonic crustaceans) contamination to MPs could make the elimination of the high molecular weight PCB smoother in comparison with animals receiving only algal food, which provides proof of the principle that MPs can act as a sink for hydrophobic organic contaminants (Grigorakis and G. Drouillard, 2018).

However, the surveillance of PCB pollutants in floating MPs requires more comprehensive research with detailed, particularly for small MPs contaminants, which could be sorbed to natural particles. Still, the scope of PCB pollutants' interaction with MPs is in the first stages of study progress. Therefore, to fully understand the effects of how MPs can act as a pollutants vector, the properties of sorption to natural particles and MPs need to be compared.

2.3. Antibiotics (ATs) and MPs

Interaction between MPs and Ats are considered the new contaminants with a high potential for adverse effects on marine ecosystems. The coexistence of MPs and ATs is an emerging concern in aquatic environments. Hence their interactions are the origin of the problem.

ATs are mainly categorized into either medical or veterinary types. ATs are medicines that treat bacterial infections in humans, plants, and animals. They act by fighting the bacteria in order to be killed, at least making it difficult for the bacteria to grow. Unfortunately, a large volume of ATs is discharged into the environment, the particulate marine system in different ways every year.

It was evident that existing MPs and Ats simultaneously in the same environment made it more polluted. MPs could adsorb the ATs, and the results may lead to uncontrollable and long-distance migration and cause complex effects. It has been approved that MPs interaction with ATs tends to be loaded with more toxicity. If swallowed by any aquatic organisms or animals below water, their combined contamination leads to higher toxicity (Wang et al., 2021).

Different MPs have different adsorption effects on ATs. These parameters could be included the polarity characteristic, density of both substances, crystallinity, glass transition temperature (the temperature at which carbon chains start to move) and point of zero charges of typical MPs. For instance, MPs with porous structure and complex hydrogen bonds have the highest adsorption capacity for ATs (Marathe et al., 2022).

In addition, various research has shown the specific factor's impacts on MPs and ATs interaction. Most MPs prefer hydrophobic interaction to adsorb hydrophobic contaminants, while hydrophobic interactions overcome the adsorption. Another important factor is hydrogen bonding, which could form between ATs (e.g., amine and carboxyl groups) and carbonaceous materials, indicating

another robust mechanism for ATs adsorption on MPs. Electrostatic interaction must also be born in mind. The interaction of the acid strength of ATs, and the point of zero charges of MPs and pH control the electrostatic interactions and impacts on the adsorption of ATs by MPs (Dong et al., 2021).

2.4. Pesticides and MPs

Nowadays, MPs are a severe problem to the terrestrial and marine environments due to dispersing uncontrollably and more obstacles as MPs can assist in sinking organic contaminants. MPs are a good candidate for adsorbents of environmental organic pollutants, pharmaceuticals, and pesticides because of their large specific surface area and hydrophobicity. The interaction of MPs with mentioned contamination can change the ecological fate.

Among all organic pollutants, as mentioned before, the study of the interaction between pesticides and MPs has an exceptional consideration due to their consumption continuously and extensively in our modern life. Pesticides are organic pollutants that can rapidly destroy the environment and control undesirable organisms. Even low concentration of pesticide usage comes with high risks to human and animal health, as well as environmental damage. Pesticides can contaminate water sources and marine ecosystems and adversely impact other life. They present different classes of chemicals with different characteristics. The behaviors of pesticides have been widely studied, but there is still a lack of information on MPs and pesticide interaction (Zhang et al., 2018).

Several mechanisms have been approved that dominate MPs and pesticide interactions in aqueous phases. However, it is still a novel field of research. Based on the available literature, it can be deduced that MPs surfaces are active agents to adsorb pesticides quickly. Then the diffusion process begins at different rates based on the properties of the pesticide and MP contacted (Hanachi

et al., 2021). For example, a study demonstrated that the sorption of pesticide (triazole fungicides type) to MPs (i.e., PS) quickly increased in the first 6 hours of interaction, and then the interaction was unchanged after 24 hours (Fang et al., 2019).

In addition, several studies have shown that the co-existing of pesticides and MPs has a significant effect on living organisms. Most studies confirmed a severe impact on aquatic organisms as MPs are recognized as contaminant vectors in marine ecosystems. It can be said simply from the study results that MPs have no significant effects on different organisms, or at least the effects are very low and negligible. However, in contrast, other studies presented MPs effects of toxicity on aquatic organisms (Hanslik et al., 2022). In simple words, generally, the interaction of MPs and pesticides increases toxicity (Peña et al., 2023).

Organochlorine pesticides (OCPs) are synthetic pesticides that have been extensively utilized worldwide. They are classified as chlorinated hydrocarbon derivatives and find broad applications in various industries and agricultural practices. These compounds are notable for their elevated toxicity, slow degradation rate, and tendency to bioaccumulate. Despite the prohibition of several OC compounds in developed nations, there has been a concerning increase in the use of these pesticides. The misuse and improper handling of these chemicals persist across continents, raising significant concerns (Ravindran Jayaraj, et al, 2016). For organochlorine pesticides, the major routes of entry to the marine environment are probably via the atmosphere, rivers, sewage outfalls, and sewage sludge.

OCPs are highly stable and bioaccumulative, and MPs are ubiquitous in the marine environment. Therefore, the interaction of this kind of pesticide with MP is likely high, as shown by studies. For instance, (Weiwei Zhang and et al. 2015) studied various kinds of organic pollutants carried with

plastic resin collected from Zhengmingsi Beach and Dongshan Beach in China. They found that the beaches have OCPs concentrations ranging from 1.2–101.5 ng g^{-1} and from 1.5–127.0 ng g^{-1}.

Once it is approved that the OCPs can be carried out by MPs, the number of research in this scope has been raised. For example, (Rios-Fuster and et al, 2021) showed that OCPs exposed to MPs enriched diets in aquaculture facilities. They reported the levels of a selection of pollutants in liver and muscle of fish (Sparus aurata) exposed to virgin and weathered MP enriched diets during three months and followed by one month of MP depuration.

Another type of pesticide is DDT, which stands for Dichlorodiphenyltrichloroethane, is a chemical compound that is colorless, tasteless, and nearly odorless in its crystalline form. It belongs to the organochloride group of compounds. While initially created as an insecticide, DDT gained notoriety due to its adverse effects on the environment. Organochlorine pesticides, including DDT, primarily enter the marine environment through agricultural use, resulting in inputs from water and air. Despite the prohibition of DDT in Western nations since the 1970s, its presence can still be detected in marine ecosystems due to its remarkable stability (with a half-life of 15 years), illegal usage, or usage in other regions (such as third world countries). DDT undergoes metabolic conversion to a similarly toxic compound called dichlorodiphenyldichloroethylene (DDE). Therefore, to evaluate the risk of DDT exposure, the combined levels of both contaminants must be considered. Additionally, a high DDT/DDE ratio suggests recent contamination.

In general, a major concentration of pollutants in liver was observed. Based on the analysis of OCPs, the concentration of total DDTs in the liver was found to be two or three times higher. However, levels of OCPs in the muscle showed greater variation among different treatments and sampling periods. Interestingly, the MP index displayed a negative correlation with

hexachlorobenzene (HCB) levels and a positive correlation with p,p′ DDT levels in the liver. Furthermore, the levels of pollutants were found to be associated with biological factors such as the overall size and weight of the organisms. These findings indicate that the accumulation of pollutants is influenced by the molecular structure of the chemicals and that MPs may be linked to the detoxification system (Rios-Fuster and et al, 2021).

2.5. Per- and Polyfluoroalkyl Substances (PFASs) and MPs

PFAS are a diverse group of synthetic chemicals that have been utilized globally in consumer goods since approximately the 1950s. They are incorporated into various everyday items. For instance, PFAS are employed to prevent food from adhering to packaging or cookware, impart stain resistance to fabrics and carpets, and produce highly effective firefighting foam. PFAS concentrations reported and short introduction on their toxicity to marine species.

PFAS compounds consist of a series of interconnected carbon and fluorine atoms. Due to the exceptional strength of the carbon-fluorine bond, these chemicals exhibit high resistance to environmental degradation. The global presence of PFAS and their connection to climate change have garnered significant attention. PFAS have been detected worldwide, spanning from polar regions to the global oceans. The oceans, known for their capacity to absorb atmospheric carbon, have become a significant carbon sink, absorbing approximately 24% of global CO2 emissions. However, due to the widespread use of PFAS in various products and inadequate waste management, they have become ubiquitous pollutants of emerging concern. Marine PFAS pollutants pose a threat to the ocean's carbon cycle and can have harmful effects on gas exchange, leading to increased greenhouse gas emissions and contributing to global warming and climate change (Barhoumi et al, 2021). This paper focuses on the impact of marine PFAS on carbon

sequestration in the oceans. These pollutants can adversely affect phytoplankton growth and photosynthesis, disrupt zooplankton development and reproduction through toxicity, impact marine biological diversity, and influence the carbon stock of the oceans, posing a threat to carbon sequestration. However, further research is needed to explore the extent and scale of this impact and uncover hidden dimensions associated with this issue (Mahmoudnia, A., 2023).

Several recent reviews have examined the sorption behavior of various organic and emerging contaminants, including PFASs, on different sorbents in sorption experiments such as (Alimi et al., 2018; Gagliano et al., 2020; Zhang et al., 2019). However, the majority of papers believe that hydrophobic interaction; electrostatic interaction; pore blockage; electrostatic repulsion; site competition; Partition effect; and natural organic matter are the factors that can make an interaction between MPs and PFASs, as displayed the factors on Figure 7.

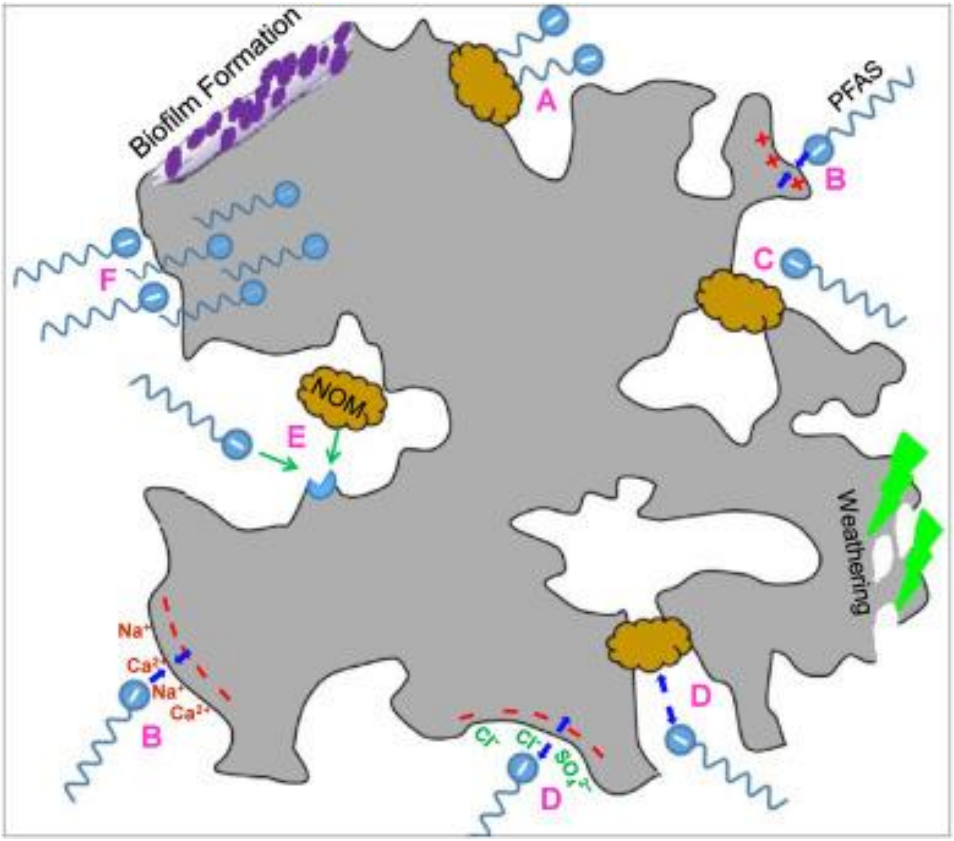

Figure 7. Factors affecting the interactions between PFASs and microplastics (Gagliano et al., 2020). A: hydrophobic interaction; B: electrostatic interaction; C: pore blockage; D: electrostatic repulsion; E: site competition; F: Partition effect; NOM: natural organic matter.

The terms "sorption" and "desorption" are commonly used to describe the movement of chemicals between different phases. Sorption refers to the transfer of chemicals from one phase (fluids) to another (solids) and can involve two processes: adsorption and absorption. Adsorption occurs when chemical molecules are attached to the solid-liquid interface through various interaction forces such as hydrophobic and electrostatic interactions, Van-der-Waals, ionic, steric, and covalent bonds. On the other hand, absorption takes place when the chemical molecules penetrate

the solid matrix and are retained by relatively weak Van-der-Waals forces, mainly through the partition effect.

In general, adsorption processes are dominant when the environmental concentrations of chemicals are low, due to the stronger interactions with the sorbent's surface. However, at high concentrations, absorption becomes more significant because of the larger volume available to accommodate the chemical molecules. Since adsorption and absorption processes often occur simultaneously, it is challenging to distinguish between them. Desorption, on the other hand, refers to the release of chemicals from MPs particles into another medium. It involves two mass transfer processes: internal mass transfer (IMT) and external mass transfer (EMT). IMT relates to the internal diffusion of the chemical within the MPs particles, while EMT involves the transfer of the chemical from the MPs particle to the surface of the plastic in the release medium. Regarding the sorption of (PFASs) on MPs, electrostatic and hydrophobic interactions are considered the dominant mechanisms, while hydrogen bonding, Van-der-Waals interactions, and the partition effect are less significant. Additional steric effects have been suggested to explain the high concentrations of short-chain PFASs sorbed on beached MPs.

During the adsorption process, various adsorption mechanisms typically work together. The specific sorption mechanisms are influenced by the characteristics of the per- and polyfluoroalkyl substances (PFASs) being adsorbed on MPs, as well as the properties of the MPs themselves and the chemistry of the solution. Electrostatic interactions occur between anionic PFASs and positively charged MPs. Therefore, changes in ionic strength (such as the presence of inorganic anions) and pH in the solution can impact the efficiency of adsorption due to electrostatic attraction or repulsion. The electrostatic negativity of PFASs is derived from functional groups like

sulphonate, sulphonamide, or carboxylic groups, while hydrophobic interactions are associated with the C-F chains in PFASs. As a result, electrostatic interactions appear to be the primary mechanism for adsorbing short-chain PFASs, whereas longer PFASs are more likely to be adsorbed through hydrophobic interactions.

In a study conducted by (Llorca et al. in 2018), the adsorption isotherms of 18 per- and polyfluoroalkyl substances (PFASs) onto three types of MPs (HDPE, PS, and PS-COOH) were investigated in both freshwater and seawater environments. The findings indicated that the majority of the compounds followed the Freundlich model, which suggests that the adsorption sites for PFASs on the MPs were heterogeneous.

The heterogeneity of adsorption sites suggests the involvement of various adsorption mechanisms, including hydrophobic interactions, Van-der-Waals forces, hydrogen bonding, and electrostatic interactions. These mechanisms likely contribute to the adsorption of PFASs onto the MPs and can vary depending on the specific properties of the PFASs and the MPs, as well as the surrounding environmental conditions.

Naturally occurring organic matter (NOM), which encompasses a wide range of organic compounds such as proteins, fulvic and humic acids (FA and HA), carboxylic and amino acids, can have complex interactions with the sorption of both long- and short-chain PFASs on MPs. The presence of NOM in the environment, alongside MPs, can lead to structural changes in the MPs over time. Depending on the concentration and nature of NOM, the molecular size of NOM, and the properties of the sorbate and sorbent, this can either inhibit or enhance the sorption of contaminants like PFASs on the surface of MPs. Most laboratory experiments have shown that the presence of NOM decreases the sorption of PFASs on various sorbents. This decrease may be

attributed to competition for active sites or pore blockage caused by NOM. However, there have been instances where the presence of NOM has led to an enhancement of sorption, particularly for long-chain PFASs on specific sorbents like anion exchange and granulated activated carbon. This enhancement is thought to occur due to the formation of PFAS aggregates or NOM-PFAS complexes (Wang et al, 2020).

Apart from NOM, the oxidation process during weathering can introduce oxygen-containing groups to the polymer structure of MPs, increasing their polarity and consequently reducing the sorption of more hydrophobic PFASs. Aging and weathering can also disrupt the crystalline regions of MPs, resulting in the formation of more rubbery domains that enhance sorption. The formation of biofilms through the attachment of microorganisms to MP surfaces can alter the density of MPs and act as an additional sorbent. Biofilm formation can modify the sorption behavior by competing with PFASs for adsorption sites and influencing abiotic aging processes. Additionally, microorganisms on MP surfaces can facilitate biodegradation, leading to smaller particles with higher surface-to-volume ratios and increased sorption capacity. The presence of other chemical contaminants in the environment can also impact sorption by competing for sorption sites on MPs. Studies have shown competitive sorption between different contaminants, such as phenanthrene and DDT, on different types of MPs. The sorption of phenanthrene was found to be higher than that of DDT on PVC and PE MPs, indicating competition for binding sites and limited sorption of phenanthrene to PVC. The presence of pyrene was also observed to decrease the sorption of phenanthrene to PE, PS, and PVC MPs. However, no studies have specifically investigated competition for sorption sites between PFASs and other contaminants (Ateia et al., 2020).

In conclusion of section 2, the interaction between MPs and organic co-existing contaminants in marine environments is a complex and multifaceted issue. Understanding this interaction requires a comprehensive investigation of the properties of both MPs and the organic compounds involved. Physicochemical properties such as density, surface area, and polymer type of MPs play a crucial role in the sorption and adsorption processes. Chemical properties of organic contaminants, such as molecular weight and hydrophobicity, also influence their interactions with MPs.

Studies have shown that various organic contaminants, such as PAHs, PCBs, ATs, pesticides, and PFASs, can sorb to MPs in marine environments. The sorption mechanisms include hydrophobic interactions, electrostatic interactions, hydrogen bonding, and Van-der-Waals forces. The adsorption behavior can be influenced by factors like the presence of naturally NOM, weathering of MPs, and competition with other contaminants for sorption sites.

PAHs, known for their adverse impacts on marine species, show a strong interaction with MPs, with adsorption capacities influenced by MP polymer type and size as well as seawater temperature. PCBs, which are inheritance contaminants, have been detected in floating MPs, and their interaction can lead to higher toxicity and long-term negative effects on marine organisms. ATs, the new emerging contaminants, can also be adsorbed by MPs, leading to higher toxicity when ingested by aquatic organisms. Pesticides, widely used in modern life, are good candidates for adsorption on MPs due to their hydrophobic properties. PFASs, known for their resistance to environmental degradation, have been detected worldwide and can interact with MPs through various mechanisms.

It is evident from the literature that the interaction between MPs and organic co-existing contaminants is not only a problem of pollution but also poses potential threats to marine

ecosystems and human health. However, the research in this field is still in its early stages, and more comprehensive studies are needed to fully understand the extent and consequences of this interaction. Efforts should be made to address the sources of MPs and organic contaminants in marine environments and develop strategies for their mitigation and proper disposal. Therefore, addressing the issue of MPs and organic co-existing contaminants requires a multidisciplinary approach involving scientists, policymakers, industries, and the general public. By understanding the complexities of this interaction and implementing effective measures, we can work towards minimizing the impact of MPs and organic contaminants on marine ecosystems and human well-being.

3. Impacts of ocean conditions on the co-existing contaminant interaction

3.1. Salinity

Both in the aquatic and terrestrial ecosystems, there is a strong visual association between the offshore limit of the largest concentrations of debris and the bottom salinity front (Eduardo et al., 2023). The majority of marine microplastics come from bigger plastic waste left on land (Andrady, 2011). MPs are easily mistaken for food by marine biota and eaten by them, much like sediments and planktonic creatures might be (Lima et al., 2014). Water pollutants including persistent organics and metals can be absorbed by MPs (Brennecke et al., 2016).

Salinity has an impact on how MPs are distributed geographically in river estuaries because it causes stratification and mixing when fresh riverine and salty saltwater flows enter the system (Vermeiren et al., 2016). According to research by Yang et al. (2009), salinity had an effect on sorption for pH levels below 7, but not for higher pH levels. While alkaline circumstances

encouraged the development of inner sphere complexes, which are not greatly affected by salinity, acidic conduction largely resulted in sorption via ion exchange and/or electrostatic attraction as outer sphere complexes. The salinity of the solution, however, affects the outer sphere complexes (Malamis and Katsou, 2013).

Marine waters get completely ejected from the estuary during the ebb tide for situations with significant discharge (Defontaine et al., 2019). The electrostatic repelling force between particles gets reduced by an increase in salt, which causes particle aggregation. The particle size, density, and structure are affected by this aggregation, which also impacted the particle's transport behavior. The interaction influences the salinity in the estuary and may, thus, impact the buoyancy of MPs, although several studies showed no correlation between MP abundance and salinity (Rodrigues et al. 2019).

Salinity effects vary depending on the electrostatic contact or ion exchange occurs during sorption. Salinity significantly reduces the adsorption of organic contaminants on MPs, and it is discovered that virgin MPs sorption ability for ciprofloxacin decreased as salinity rose (Liu et al., 2019). Various studies have found that MP absorption and abundance are influenced by the ocean's depth as well as salinity, which significantly varies with ocean depth. According to Zhou et al., 2021, MP and its sorption ratio can be impacted by higher salinity. As seen in Fig. 7, the abundance of MPs has increased at every single sample station as salinity has increased. According to Goedecke et al. (2017), increased salinity had a negligibly positive effect on the difenoconazole adsorption on virgin polyamide (PA) and PP but delayed adsorption in PS.

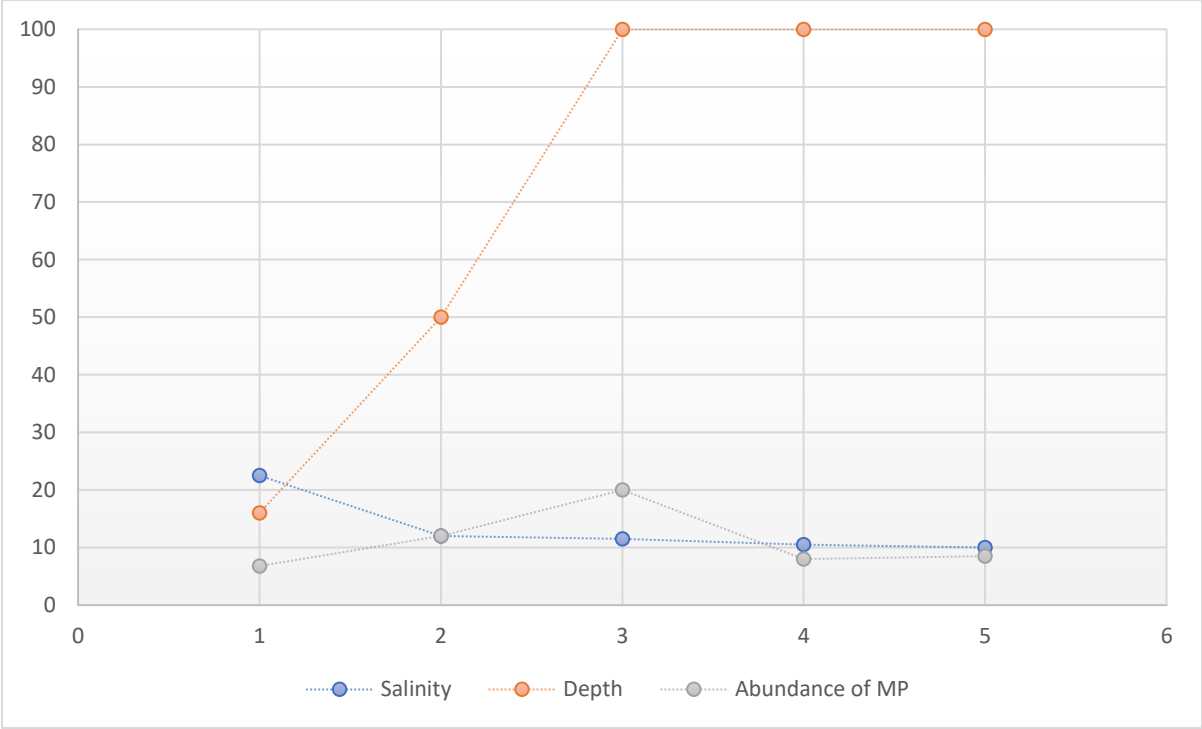

Figure 8. Changes in microplastic abundance with salinity over depth in the water (Zhou et al, 2021).

It was demonstrated in research by Zhang et al. (2019) that the salinity's impact on the sorption of carbazole on PP varied. The adsorption capacity and rate initially decreased with increasing salinity, but they eventually increased again and peaked at a salinity of the solution of about 14%.

A research on Baltic Sea (Maciejewska et al., 2019) has shown that Salinity level can vary from point to point and absorption can get affected by that. Salinity has effects on floating of co-contaminant as it gets dissolved, absorbed or sunk (Uurasjärvi et al., 2021). Most of the research found that the ability of metals to sorb water dropped dramatically as salinity increased (Acosta et al., 2011), however some have shown that salinity had only a little effect or even a beneficial effect on sorption. The sorption of Cu, Cd, and Pb in aquatic solutions was examined in recent research (Wang et al., 2020) that looked at the impact of various interfering cations such Mg^{2+}, Ca^{2+}, and

K^+. When an inhibitory impact on the removal of metal ions was rated from strong to weak, Mg^{2+} was shown to have a larger competitive effect than monovalent cations (Narges, et al., 2022). Hydrophobic interactions have been reported as the dominant type of bonding in the case of POPs (Wang et al., 2020). In the case of cyanotoxins like microcystin LR, the sorption was negatively correlated with the particle size and had little effect due to pH and salinity (Moura et al., 2022). Changes in co-contaminant bioavailability occur based on sorption affinity and kinetics, meaning that a contaminant that was previously freely accessible in the surrounding media is now absorbed onto MPs (Marchant et al., 2022).

As a lot of studies still have their point of view to believe that salinity can be neutral according to their to the type of salt or presence of certain salt, more study needed to be done to get a proper opinion on it.

3.2. Temperature

Since the oceans make up 71% of the planet's surface, scientists keep track of sea surface temperatures (SST) to learn more about how the oceans and atmosphere interact. Solar radiation, or the energy that comes from the sun, warms our world. Due to the Earth's spherical shape, the angle of the surface with respect to the incoming radiation varies with latitude. Direct overhead sunshine received throughout the year heats surface waters at low latitudes close to the equator. Ocean waters in high latitudes receive less sunlight and only 40% of the heat that is produced near the equator. Because of these differences in solar radiation, the ocean's surface temperature may vary, ranging from a balmy 30°C in the tropics to a bitterly frigid -2°C towards the poles. This surface temperature varies depending on the season in certain places while remaining quite steady in others. According to GESAMP, a rapid rise in temperature could have a cascading effect on the environmental fate, transport, and cycling of pollutants by causing sea levels to rise, coastal

erosion, an intensification of hydrological cycles, and extreme events (cyclones, heat waves, and forest fires). After being released into the environment, MPs and organic contaminants may age more quickly when exposed to high temperatures and other active media, which can significantly alter the surface morphology, microstructure, and environmental behavior of common pollutants (Lambert and Wagner, 2016).

Table 1. Studies on organic co-contaminant by influence factors

Authors	**Co-contaminants**	**Influencing Factor**	**Accountability**
Ahmed et al, 2019	Microplastic	Temperature	Toxic Circumstances
Panther et al., 1999	PAH	Temperature	Seasonal Variation
Eilertsen and Taasen, 1984	POPs	Temperature	Seasonal Variation
Schwarzenbach et al., 2003	PCB	Temperature	Water Solubility
Isabel et al., 2015	PAH, PCB, PBDE	Temperature	Water Solubility
Simoneit et al., 1993	Organic components	Temperature	Immature Organic Detritus

According to Ahmed et al, 2019, to evaluate the effect of temperature using different kinds of water under toxic circumstances, batch tests were carried out at three different temperatures, 20, 25, and 30 2 °C, to evaluate the impact of temperature on the removal of Microplastic during the RBF process. Temperature had a significant impact on the way microplastic broke down. The study found that temperature affected the attenuation of 5 out of the 13 pesticides that were chosen. Based on Panther's findings in 1999, the distribution of smaller molecular weight species in gases and particles is altered by temperature, which is a significant factor that may affect PAH quantities in the atmosphere. Due to enhanced volatilization, more of the smaller PAHs will be found in the

gaseous phase during the summer months at higher temperatures. The likelihood of spending time in nature is relatively low during the rainy season. In 1984, Eilertsen and Taasen stated that it explains that the environment and the fate of POPs are influenced by physical and biological variables, such as low temperatures and short growth seasons. When the sun comes out again and the temperature rises in the spring, primary output increases quickly. PCB partitioning and water solubility are both influenced by temperature (Schwarzenbach et al., 2003). By using the van't Hoff equation and the assumption that the temperature dependence of organic matter/water partitioning is equal to that of octanol/water partitioning, the observed BAFs were corrected for the temperature effect, allowing a direct comparison between the arctic (Barents Sea) and temperate (Baltic Sea) food webs:

Equation 1: $$ln(K_{pw}(T_2)) = ln(K_{pw}(T_1)) + \frac{\Delta H_{pw}}{R} \bullet \left(\frac{1}{T_2} - \frac{1}{T_1}\right)$$

where How is the enthalpy change of phase transfer (J mol), R denotes the gas constant (J mol 1 K deg 1), T denotes the sample temperature (K), and Tref denotes the reference temperature (298.15 K). The values for "How" came from Li et al. (2003).

Equation 2: $$\mathrm{BAF} = \frac{\mathrm{BAF}_{\mathrm{salt}}}{10^{K^S[\mathrm{salt}]}}$$

The impact of temperature may grow for bigger molecules since ΔHw increases with increasing molecular weight (DiFilippo and Eganhouse, 2010). The degree to which ΔHpw differs among the various polymers determines whether there are variations in temperature sensitivity between plastic kinds (Isabel et al., 2015). According to data for PAH in LDPE and PDMS (Booij et al., 2002; Muijs and Jonker, 2009; Adams et al., 2007), changes in water solubility play a more

significant influence than changes in plastic solubility. Investigation is still needed to see if this holds true for additional organic materials (Isabel et al., 2015). According to Simoneit (1993), in these high temperature and fast fluid flow hydrothermal regimes, organic matter modification, mostly reductive and often from immature organic detritus, occurs. These chemical modifications, exhibition, and migration are caused by hot, flowing water (temperature range: warm to > 400 °C) (Simoneit et al., 1993).

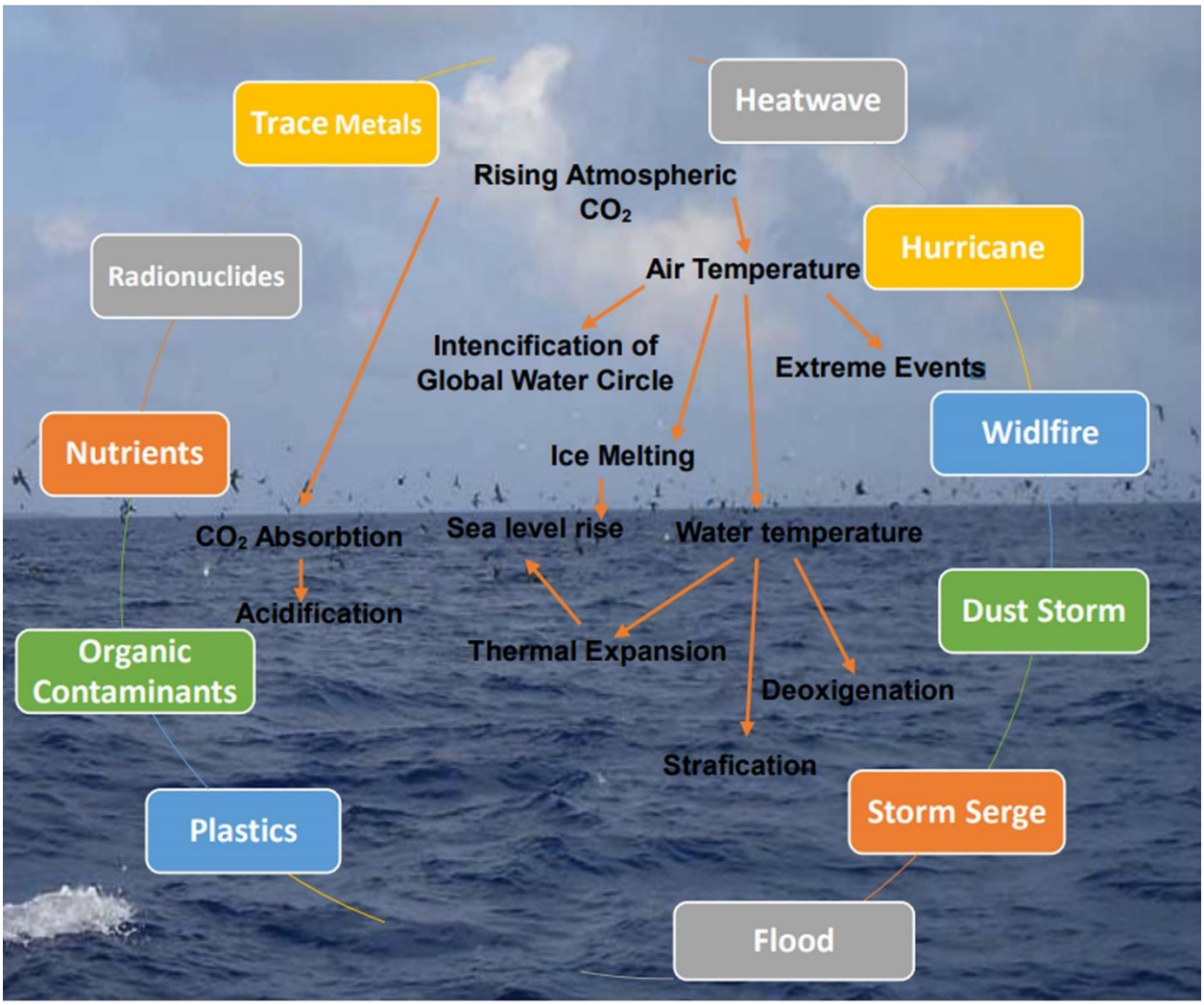

Figure 9. Factors contributing to temperature affecting (Simoneit et al., 1993).

Figure 9 demonstrates the factors that are contributing to temperature affecting a variety of natural phenomena, including air, land, and water bodies. Different kind of natural phenomenon are involved incressing temperature of the waterbodies through rising CO_2 , air pressure or by melting ice. It creates water pressure which leads to thermal expansion, deoxygenation, and stratification. Nutrients, organic contaminants and MPs gets affected by these factors and changes their form to dissolve in. Most of the absorption research considered ambient temperature. Elevated temperatures, however, can cause chemical reactions that are distinct from those that occur normally (Tidjani, 2000).

A connection between temperature and bacterial processes and infections may influence antibiotic toxicity (Acuna et al., 2015; Burnham, 2021). The ability of POPs to bind to MPs is influenced by the water's temperature (reference). Despite some substances becoming less soluble as temperature rises, surface tension does in fact decrease (Gateuille et al., 2022). These two processes result in a rise in sorption when the temperature falls (Zhan et al., 2016). Laboratory studies show that temperature has only a small effect and that, depending on the sorption processes involved, a maximum absorption may occasionally be observed at temperatures between 15-20 °C. Higher aqueous solution temperatures promoted higher adsorption; however, higher pH, dissolved organic matter, and nutrients in biochar-based micro(nano)plastics might make alternate outcome because of negative reacting mechanism at adsorption. This observation is supported by the fact that, in the majority of cases, the effect of temperature is thwarted by the opposing effects of other reactive agents present in the waterbody. The aging of MPs can be accelerated by high temperatures, and other environmental agents that are active in the environment. This can significantly change the surface morphology, microstructure, and environmental behavior of typical contaminants (Lambert and Wagner, 2016).

According to certain research, an increase in temperature has an impact on ecosystem functioning at the molecular level and might alter the sensitivity of marine creatures. In a study by Ding et al., 2020, the characteristics and mechanisms of the adsorption of organic pollutants with various physical and chemical properties on aged MPs were investigated. The absorption along with alteration were evaluated by adsorbing polycyclic aromatic hydrocarbons and antibiotics, which are relatively common organic pollutants, which result in favor explaining higher temperature, influences absorption. Only a few pollutants react uniformly to temperature, according to research by Abdelrady et al. from 2019. This research sought to understand temperature as a waterbody influencer. Some molecules dissolve more readily than others; for instance, at higher temperatures, naphthalene, fluorene, and anthracene showed lower interaction values. According to research, cold temperatures increase bacterial richness while reducing catabolic diversity in the microbial community (Bargiela et al. 2015).

LiberalChemisty has done tests for the solubility fluctuation with temperature for a wide range of substances. In relation to temperature, the solubilities of various inorganic and organic solids in water. Temperature may affect solubility in either a positive or negative way; the strength of this temperature dependency varies significantly between substances. Sucrose and glucose are the two organic co-contaminants on which we can concentrate. The data chart shows that sucrose is already soluble between 0 and 20 degrees Celsius, and that after 25 degrees, it becomes soluble between 200 and 250 degrees Celsius. In the case of glucose, solubility is steady from 0 to 10 °C and increases significantly from 75 to 250 °C (15 to 60 °C).

3.3. Mixing energy

Most of the floating plastic collects in regions known as "trash patches." To conduct an in-depth analysis of the problem and create solutions, it is essential to understand the mechanisms influencing the movement and fate of plastic in the water (Imani, 2021) According to Yang et al. (2022) tidal movements in the open ocean may affect the movement of coexisting organic and MP contaminants. To help with the creation of transport models, it is important to investigate how these contaminants move and are distributed when subject to barotropic tidal currents. To better understand the deep ocean transport pattern of PAH, PCB and MPs, it is possible to use barotropic tidal currents in simulations to account for MPs' transoceanic movement (Sterl et al. 2020). The method involves numerically simulating the advection of fictitious plastic particles in order to study the effects of barotropic tides on the movement and accumulation of floating microplastics (Sterk, 2020).

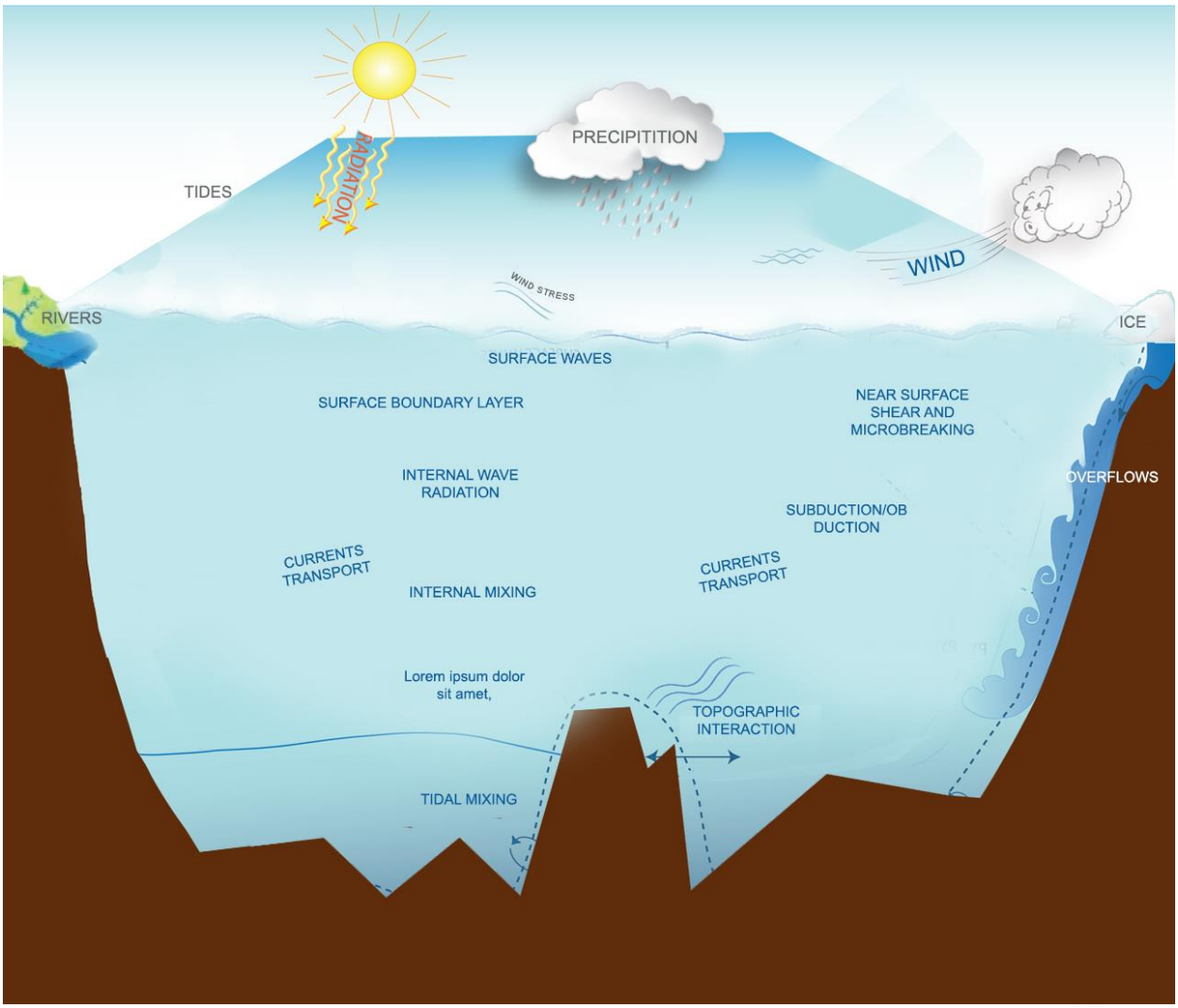

Figure 10. Different sources of energy contribute to the evolution under water (Wang et al., 2016).

Figure 10 shows how different sources of energy can contribute to the evolution under water through tide, precipitation and wind, which can trigger the surface waves producing internal wave, internal mixing or underwater current movements. These process controls the internal mixing, micro-organism breaking including total mixing with topographic wastes abandoned on see bed.

The three most important physical processes that affect how coexisting contaminants are transported in estuarine ecosystems are tide, runoff, and wind (Wang et al., 2016). The flow field

has a significant impact on the distribution of their co-existing contaminants MPs (Zhang et al., 2020). Because the terrain varies from place to place, the flow velocity during flood and ebb tides is very asymmetric. An example of a reverse flow is tidal flow. Particularly during a storm, stronger waves remove more co-existing contaminants from the sediment, and the effectiveness of vegetation at dampening waves and the depth of burial both affect the contaminants' retention (Sterk,. 2020). According to Geng et al. (2017), there is a large prevalence of localized aquifer pollution brought on by inadvertent pollutant discharge from various sources. Additionally, organic impurities in the water, it has an impact on microplastics. The complex hydrodynamics in coastal aquifers, which are a result of oceanic forcing in the form of tidal fluctuation and wave setup, along with the density difference between seawater and fresh groundwater and the associated buoyancy forces, have an impact on the transport of PAH and PCB (Brovelli et al., 2007). The density differential between ambient groundwater and contaminated plumes further complicates the migratory pattern of the plumes (Zhang et al., 2002).

Numerous methods can lead to the introduction of organic contaminants like PAH and PCB into the coastal environment, where they are then subject to biogeochemical cycles, sinks, and bioaccumulation processes. a coastal water body's whole organic pollution cycle. Their inputs may result directly from industrial, aquaculture, urban run-off, and other human activities, or indirectly from atmospheric deposition or river and run-off runoff. The physical-chemical characteristics of the pollutant, the amount of aerosol deposition, and the precipitation regime will all affect how dominant the atmospheric deposition process is. Many organic contaminants have a strong affinity for organic materials to which they bind because they are hydrophobic (Jurado et al. 2004).

In a coastal aquifer affected by density-driven flow and tidal force, Aref et al., 2022 discovered a sequential data assimilation method to produce assessment of the features of the contaminated

source. They also found that the tidal force, which creates a more complex flow field, makes it slightly more difficult to estimate unknown contaminant source variables than it would be in the absence of an oceanic force, and that this increased difficulty manifests as slightly higher estimation errors and uncertainties (Aref et al., 2022).

3.4. Suspended particles

Seawater's suspended particles, which include mineral and biological particles, are crucial because they transport the majority of the ocean's contaminants and nutrients. The concentration, floc size, and contents have a big impact on the optical characteristics of sea water and the marine biological environment (Dinghui et al., 2019). Most suspended particles in estuarine and coastal environments take the form of flocs that participate in the frequent flocculation and break-up processes that happen because of the dynamic physical environment. (Dinghui et al., 2019). Suspended particles have been the subject of research for more than 50 years, and it is now unmistakably established that SPMs are a significant contributor to the decline in water quality that affects aesthetics, raises the cost of water treatment, decreases fisheries resources, and seriously degrades aquatic ecosystems (Bilotta et al., 2008).

To increase their affinity to additional pollutants, PM-type compounds are also used as adsorbents in the water purification or sediment remediation processes. In light of the presence of PMs, Velzeboer et al. (2014) investigated the sorption behavior of PCBs on organic matter (OM), nanoplastic PS, and microplastic PE. They discovered that the affinity for PCBs in OM and micro-PE was comparable, and that the isotherms were well fit by linear forms, indicating that surface adsorption was less important than partitioning into the bulk polymer. The sorption capacity of PCBs was an order of magnitude more than that of OM and micro-PE, but that of PS was an order of magnitude lower 2019 (Yu et al.).

According to Teuten et al. (2007), MPs' large specific surface area and hydrophobic surface, which have a strong affinity for organic or inorganic pollutants, are the main causes of the adsorption of pollutants. The most significant organic pollutant adsorbents are thought to be organic materials in sediment and soil. The concentration of organic pollutants on plastics in waterbodies, according to some studies, is hundreds of times higher than that in sediment (Teuten et al., 2007). It has been stated that antibiotics can be successfully adsorbed by MPs (Li et al., 2018). Various contaminants, some of which might be harmful to aquatic life, are carried by SPM and MPs. The unfavorable effects are brought on by the cumulative effects of these vectors or perhaps a synergistic interaction between vectors and pollutants. The negative effects may be linked to these interactions due to the fine fractions (silt-clay) of the SPM and sediments' large surface area, which serve as an ideal location for the accumulation of heavy metals and other hazardous compounds (Souza Machado et al., 2015). High concentrations of suspended solids in the water column may also have a negative effect on the biodiversity of the marine and coastal environments. Additionally, according to Wang et al. (2017), the modification of MPs' surfaces is connected to the interaction of MPs with metals in the marine environment.

According to the article provided by Anna et al., 2021, absorption of PAH, PCB and HCB increase because of suspended particles mixed in ocean body. The ratio of absorbing organic contaminants was significant by the SPM, which is why being advised to do more research on how creatures living there react to the toxins detected in this study since this might endanger pelagic and benthic organisms (Anna et al., 2021). According to another article, large quantities of pollutants are deposited and retained in coastal wetlands close to populated areas from several sources, including as air deposition, riverine inputs, and direct or indirect discharges. In the aquatic environment, sediments and suspended particulate matter easily bind with PAH, PCB, and HCB, which may

result in secondary contamination sources (Harikumar el al., 2023). Heavy metals are one of the primary contaminants found in estuarine habitats. They can come from both natural and artificial sources, have negative long-term effects on the ecosystem, and endanger living beings. Its transformation into dangerous compounds after absorbing organic pollutants is quite concerning. Terrestrial runoff is one of the most common ways that metals reach the coastal environment. In addition to being loaded with heavy metals, the sediments also included other dangerous organic contaminants (UNEP, 2001).

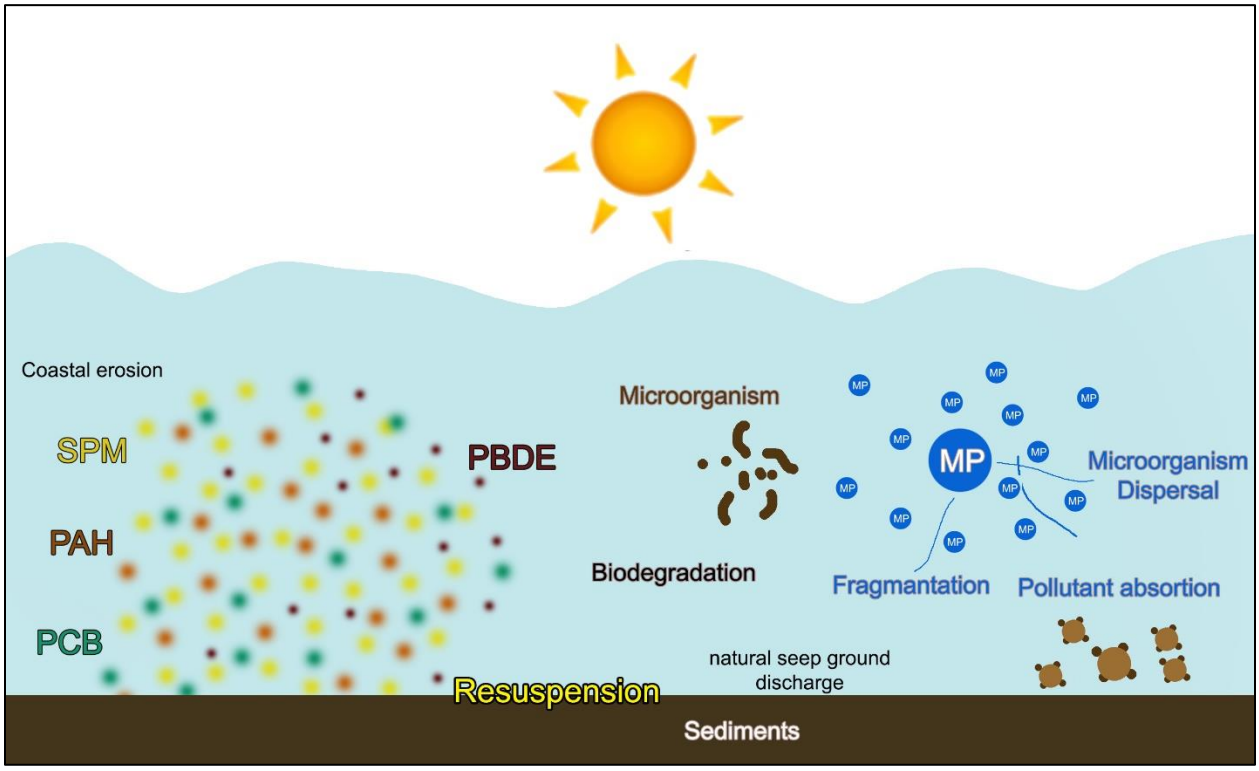

Figure11 . Suspended Particles, Microplastic and co-contaminants in ocean

Figure 11 provides a detailed understanding of the relationship and flow of several organic pollutants in the presence of microplastic, sediments, and SPM. Most PAH or PCB is fully absorbed by suspended particles, which explains why they are present in water as a mixed and

novel substance. Following their descent to the earth's surface, they build up in sediments at the bottom, where they can bioaccumulate and have an impact on aquatic life (Jesus et al., 2022).

3.5. pH

Examining how pH affects the sorption of MPs is crucial given the acidification of the marine ecosystem. As pH increases, HDPE loses some of its ability to sorb Pb, Ni, Co, and Cd. While Cr and Cu have increasing and constant sorption capacities, respectively (Holmes et al. 2014). A particular pH is required for electrostatic interaction (Wang et al., 2020). For the negatively charged surface of the MPs to electrostatically attract positively charged organic pollutants, the pH of the adsorption environment must be greater than the zero point of charge of the MPs. The organic pollutants will, however, become deprotonated and exist in an anionic form, causing electrostatic repulsion and impeding MP adsorption when the pH of the adsorption environment exceeds the acid dissociation constant of the pollutants (Wu et al., 2019). Even though it has been demonstrated that the pH of the surrounding water influences the pollutant sorption by MPs, such as through protonation, there is a need for a more thorough comparative or statistical approach to gain insights into the associative patterns of pH with MPs and pollutants (Guo et al. 2018).

According to a 1997 study by Fabrizio et al, the pH level in marine water has a variable impact on the absorption, dissolution, and mixing of co-contaminants. The highest value for sediment and water is frequently at pH 6.5, while the highest value for marine samples is typically at pH 5.0, which is indeed a small difference, they added. The pH range between pH 5.0 and pH 8.0 only weakly affects and does not have a fixed trend with changing pH for sediment and water (Fabrizio et al 1997). According to Guo et al. (2018), the amount of TYL increases as pH decreases,

improving the ability of PS and PVC to bind the antibiotic tylosin (TYL), even though the absorption capacities of PP and PE don't change much. When pH falls, more PS and PE bind to PFOS, protonating the surface of the MP and increasing the amount of anionic PFOS produced. According to Wang et al. (2015), the PE surface might also be easier to protonate than the PS surface. PET might turn toxic because of pH variations in the ocean altering the chemical equilibrium of MPs by speeding up or slowing down chemical leaching from their surface (Piccardo et al., 2020). Rong et al 2019 were involved in e research where they worked on organic pollutant degradation over a wide pH range and found some amazing factors. Most of the time, the catalytic process is very active in acidic environments, whereas it is hindered in neutral or alkaline environments. However, throughout a broad pH range, HS-CuFe2O4-exhibited excellent catalytic activity (Rong et al 2019). Initially starting at a pH of 3.0 and rising to a pH of 9.0, the effectiveness of CIP degradation was boosted. At pH 10.0, it began to gradually fall. Additionally, at pH 3.0, the amount of copper ions that were dispersed in the solution reached a maximum of 34.4 mg/L, making up more than 25% of the total Cu dose. This indicates that the catalyst may have lost some of its copper, which would have caused the OVs to vanish. The solution under acid, however, had only a very little amount of iron ions (Rong et al 2019).

Co-contaminant adsorption decreases with rising solution pH, according to various studies (You et al., 2010), and the presence of solution pH may have an impact on adsorption effectiveness (Du et al., 2014). According to a case study (Zhan et al., 2016) on PCB sorption on MPs in synthetic seawater, the capacity of sorption increases with smaller MP particle sizes and seawater exhibits the greatest PCB sorption on MPs when compared to other solution environments. According to Hofmann et al (2016), MPs (microscale polymer particles) were discovered to adsorb organic molecules in the order of increasing inclination.

However, it is abundantly obvious that pH does have some bearing on the destiny and transit of microplastics and organic co-contaminants through its contribution to the ocean water's dissolving capacity, speed, and duration. varying conditions and studies have revealed varying performances of pH. In order to gain additional insights, more research must be done.

3.6. MP weathering

According to Ferguson et al. (2010), weathering is a crucial factor that can change the density, size, and form of MPs, which in turn alters how quickly they sink. Recent research suggests that these procedures don't all have the same effects on MP transport. For instance, have shown that exposure to abrasion, fragmentation, and biofouling on plastic and microplastic surface is the most important temporal change in physical features of plastic and microplastic (Shooka et al. 2019). Since weathering mechanisms have significant effects on the condition and behavior of the particle, they can influence how plastic debris is disposed of in aquatic habitats and sediments (Meisam et. al, 2021). Larger plastic waste that is exposed to the environment over time breaks down into smaller pieces due to mechanical breakdown, photodegradation, and perhaps microbiological deterioration. (Meisam et. al, 2021)

The bulk and surface characteristics of both primary and secondary MPs are continually changing as a result of ongoing exposure to weathering environments (Rubin et al., 2021). The addition of carbonyl functionalities, which are crucial in sorption processes (Rubin et al., 2021) is one of the most frequent weathering-driven surface changes of MPs (Liu et al., 2019; Sarkar et al., 2021). Other MP physico-chemical alterations that can be brought on by weathering include increased surface-area-to-volume ratios, eco-corona and biofilm additions (Mei et al., 2020; Rubin et al., 2021), and increased hydrophilicity (Mei et al., 2020). All of these alterations have a direct bearing

on sorption interactions and affinity towards co-existing substances. Various environmental effects are a result of MP interactions with TrOCs. TrOC sorption may further change the surface characteristics of the MPs, which may affect how the MPs interact with microorganisms and ultimately cause them to sink in aquatic environments (Chen et al., 2019). According to Wang et al. (2020), MP transport in aquatic environments will enhance the likelihood of interactions with hydrophobic TrOCs, concentrate the TrOCs on the particle surface, and ultimately raise the potential toxicity of the TrOCs toward living things. The function of MPs as a vector of environmental TrOCs has been extensively explored in recent research due to these interactions and their possible combined detrimental consequences on the environment and human health (Koelmans et al., 2016).

Mechanical fragmentation, photo-degradation, thermal-degradation, and biodegradation are the principal weathering mechanisms of MPs (Chen et al., 2019). Determining their movement, transformation, and interactions with pollutants and microbes in water and soil is a crucial procedure. Ion complexation, hydrogen bonding, and electrostatic interaction forces in weathered MPs might encourage the absorption of potentially harmful substances, such as heavy metals and metalloids (Dong et al., 2020). Mechanical fragmentation, photo-degradation, thermal degradation, and biodegradation are just a few of the weathering processes that MPs go through. Plastic debris exposed to environmental weathering are prone to degradation mainly due to photo-oxidative, thermal, and hydrolytic processes which leads to chemical oxidation, chain scission and crosslinking reactions that in most cases result in the progressive fragmentation of the polymeric material into microparticles (Gewert et al., 2015). The thermodynamic characteristics of various hydrocarbons cause significant variations in the stability of organic compounds that can be extracted from sedimentary rocks and petroleum (Prajapati et al., 2022). Some of them, particularly

the ones with biological configurations, are unstable and are cracked or changed more frequently than others as a result of isomerization and aromatization processes. The weatherhat variations in specific compound groups take place at various stages of weathering is intriguing.

According to Liu et al. (2019), MP weathering can result in the generation of hydroxyl, carboxylic, and oxygen-containing aldehyde, ketone, and hydroxyl groups. In order to influence the molecular interactions between MPs and contaminants, the oxygen functional groups improve the hydrophilicity, polarity, and surface charge of MPs (Liu et al., 2019). According to studies, weathering improved MPs' sorption capabilities for hydrophilic organic contaminants (Liu et al., 2019). Due to their enhanced surface polarity and charges, weathered MPs also showed more sorption toward metals than pristine ones (Holmes et al., 2012). Cracks develop because of weathering, and MPs' increased SSA and pore size further enhance HOC sorption and diffusivity inside the polymer backbone (Hartmann et al., 2017). Again, weathering reduces hydrophobicity and raises polarity of MPs, which reduces HOC sorption (Hüffer et al., 2018); thus, the sorption capabilities depend on which function is prominent. Previous research (Kaiser et al., 2017; Rummel et al., 2017) showed that weathering encouraged the growth of biofilm on MP surfaces. By altering their physical characteristics, such as their reduced surface hydrophobicity and enhanced heterogeneity, biofilm can influence the sorption behavior of weathered MPs (Rummel et al., 2017).

4. Toxicity of the co-existing contaminants

Microplastics are important carriers of organic and inorganic pollutants. Studies have shown that microplastics can act as a vector for transferring hazardous hydrophobic organic chemicals (HOC) to marine species (Smith et al.,2018). Microplastics in the sea accumulate persistent organic

pollutants (POPs) such as polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), and organochlorine pesticides like dichlorodiphenyltrichloroethane (DDT) or hexachlorobenzene (HCB) from the water. These chemicals can contaminate marine biota when ingested, and the marine food web might be affected by microplastic biomagnification (smith et al., 2018). Microplastic contaminants can cause acute, sub-chronic, carcinogenicity, genotoxicity, and developmental toxicity. The transfer of microplastics and their toxic components across different levels of the food chain significantly impacts the safety of marine ecosystems and human health. (Diepens and Koelmans, 2018; Miller et al., 2020). Microplastics can also interact with other contaminants such as oil, in the ocean and transfer it to marine organisms (Yuan et al., 2022).

4.1. Phytoplankton and zooplankton

4.1.1. Phytoplankton

Microplastic co-contaminants can have detrimental effects on the photosynthesis and growth of phytoplankton. Despite their small size, phytoplankton plays a vital role in marine ecosystems. They are the ocean's primary producers, using CO2 absorbed from the atmosphere or ocean to generate organic matter and oxygen through photosynthesis. Marine primary production accounts for approximately 80% of Earth's total oxygen production. Phytoplankton accounts for 45% of global primary production and is foraged by zooplankton, which then becomes a food source for predators, such as mollusks, shrimp, krill, and fish (Brierley, 2017). As a result, researchers are keen on further investigating the significance of phytoplankton due to their crucial role in oceanic carbon sequestration (Witman & Writer, 2017)

Unfortunately, the widespread presence of microplastics in aquatic environments can interfere with phytoplankton's ability to feed, consume food, and carry out photosynthesis, ultimately detrimental

to their growth, reproduction, and overall community dynamics. These negative impacts can potentially negatively affect the sustainability of entire aquatic ecosystems.

A study by Ghosal et al. (2018) found that exposure to polystyrene microplastics contaminated with phenanthrene (a polycyclic aromatic hydrocarbon, or PAH) reduced the growth and photosynthesis of the marine diatom Skeletonema costatum. The study showed that the toxicity of PAH increased when it was adsorbed onto microplastics, suggesting that microplastics can act as vectors for the transport and accumulation of toxic contaminants in the marine environment. Another investigation conducted in 2018 investigated how the diatom Phaeodactylum tricornutum reacted to plastic leachate, the chemical released when plastic breaks down in the ocean Gerecht et al., (2018). They discovered that diatoms' cell density, development rate, and photosynthetic efficiency all decreased due to exposure to plastic leachate.

The impact of co-existing contaminants of microplastics on phytoplankton can be significant. Exposure to microplastics and their associated contaminants can lead to reduced growth and photosynthesis in phytoplankton, which can have cascading effects on the entire marine food chain (Cole et al., 2018). It can also impact nutrient uptake and utilization in phytoplankton, reducing growth and productivity. Elevated levels of specific hazardous metals can lead to impairments in the endocrine system, reproductive system, and growth of marine organisms (Hylland, 2006; Jakimska et al., 2011). Co-existing contaminants such as polycyclic aromatic hydrocarbons (PAHs), and polychlorinated biphenyls (PCBs) can cause oxidative stress and inflammation in phytoplankton cells, which can impair their cellular functions and lead to cell death (Silva et al., 2018). Oxidative stress occurs when there is an imbalance between the production of reactive oxygen species (ROS) and the cell's ability to neutralize them. Organic Contaminants such as PAHs and PCBs can induce the generation of ROS within phytoplankton cells, exceeding their capacity

to detoxify or scavenge these harmful molecules. Consequently, excess ROS can lead to oxidative damage to cellular components, including proteins, lipids, and DNA. Oxidative stress is a condition where there is an imbalance between the production of reactive oxygen species (ROS) and the ability of cells to detoxify them De la Cruz-Enríquez, J., et al. (2021). Inflammation is the immune system's response to harmful stimuli such as pathogens, damaged cells, or irritants. Liu, Y., et al. (2022). Phytoplankton are important for marine ecosystems as they contribute to primary production and serve as a food source for higher trophic levels. Therefore, the death of phytoplankton due to the co-contaminants of MPs can have significant ecological consequences.

The bacteria that decompose the phytoplankton deplete the oxygen in the water, suffocating animal life and affecting the marine ecosystem (Lindsey et al., 2010). Certain species of phytoplankton produce powerful biotoxins, making them responsible for so-called "red tides," or harmful algal blooms. These toxic blooms can kill marine life and people who eat contaminated seafood (Lindsey et al., 2010). If phytoplankton were to die, it would be the end of almost all marine life on Earth. With that, a major source of our food would disappear. Without them, the capacity of our oceans to serve as carbon sinks will diminish greatly, which would further broaden the scope and impact of climate change. (Climate Conscious,2021)

Phytoplankton in natural environments are often exposed to a mixture of contaminants, including microplastics and other pollutants. The research gap lies in understanding the interactive effects and synergistic impacts of microplastic co-contaminants with other pollutants on phytoplankton. Investigating the combined effects of multiple contaminants would provide a more realistic assessment of the ecological risks and potential interactions (Auta et al., 2017).

These studies highlight the potential adverse effects of microplastic co-existing contaminants on phytoplankton, including reduced growth, photosynthesis, and cell density. Microplastic co-existing contaminants harm phytoplankton in the ocean by highlighting the potential negative impacts on primary producers and ecosystem dynamics, which can have cascading effects on marine life and carbon sequestration. Further research is needed to understand better the mechanisms and long-term consequences of these interactions and their implications for marine ecosystems.

4.1.2. Zooplankton

Microplastic co-existing contaminants are a global environmental concern, and their impact on marine zooplankton and invertebrates can have far-reaching ecological consequences. While some studies have reported adverse effects on feeding behavior, growth, development, reproduction, and lifespan, others have not observed negative effects from MPs contaminants ingestion (ACS Publications, 2020)

Microplastic pollution harms zooplankton, impacting their growth and reproductive capabilities. Zooplankton plays a vital role in marine ecosystems as the primary consumers of phytoplankton. They are responsible for nutrient recycling, biogenic element cycling, mass, energy, and genetic information flow through food chains and webs, and the breakdown of environmental pollutants. Additionally, zooplankton contributes to the decomposition of particulate organic carbon (POC) through respiration, which affects the depths at which POC is re-mineralized. This process is significant for regulating atmospheric CO2 levels and global climate change. Without the involvement of zooplankton in ocean carbon sequestration, sequestered carbon would quickly return to the water and atmosphere (Shen et al., 2020).

Zooplankton respiration releases carbon dioxide (CO_2) back into the water column, thus acting as a source of CO_2. Zooplankton excretion and egestion produce dissolved organic carbon (DOC) and fecal pellets, which can be rapidly sinking forms of carbon. These sinking particles transport carbon from the surface to deeper waters, where it can be stored or re-mineralized. (Steinberg et al., 2017)

Zooplankton contributes to carbon export through various mechanisms. They ingest lower trophic levels, produce fecal pellets and carcasses, and respire CO_2, all of which contribute to the biological carbon pump (BCP). Zooplankton contributes to CO_2 fixation in the ocean by grazing on phytoplankton and producing fecal pellets that sink to the deep sea, where they are buried or decomposed by bacteria. This process is part of the biological carbon pump, which involves the uptake of CO_2 by photosynthetic organisms in the upper ocean, followed by the sinking of organic matter into the deep ocean. (Schnack-Schiel and Isla, 2005; Turner, 2015; Steinberg and Landry, 2017). Additionally, zooplankton actively transports carbon below the thermocline during daily migration and seasonal descent to overwinter at depth (Halfter et al., 2020). Zooplankton behavior and activities influence the fate and distribution of carbon in the marine environment. They can consume or break up clumps of carbon-rich material sinking from the surface ocean, particularly in areas with high oxygen levels (Steinberg et al., 2008).

However, the widespread presence of microplastics in the ocean may disrupt this balance. They typically consume MPs contaminates that could cause a trophic transfer of contaminates via the food chain resulting in bioaccumulation negatively impacting higher trophic organisms (He et al., 2022)

Zooplankton consists of a diverse range of marine organisms, both vertebrates and invertebrates. They can be classified into holoplankton, which complete their entire life cycle in the plankton, and meroplankton, which have larval stages. Zooplankton plays a crucial role in transferring energy through the food web by consuming phytoplankton. They are particularly active in surface waters, where the concentration of microplastic contaminants is elevated. Consequently, their exposure to and ingesting microplastics are more likely to occur in these areas. (Cózar et al., 2014)

Co-existing contaminants of MPs have adverse effects on zooplankton, including reduced survival, growth, and reproductive success and accumulation of the pollutants in the tissues of zooplankton that can be transferred up the food chain. Research indicates that contaminants such as polycyclic aromatic hydrocarbons (PAHs), phthalates, and heavy metals have toxic effects on zooplankton. For instance, Lin et al. (2018) found that exposure to microplastics and PAHs decreased survival and reproduction in the marine copepod Tigriopus japonicus. Cole et al. (2011) also demonstrated that exposure to microplastics and related chemicals led to reduced feeding and growth rates in the marine copepod Calanus helgolandicus. Moreover, the presence of microplastics can amplify the toxicity of the co-existing contaminants, as shown by Koelmans et al. (2016), who found that microplastics increased the bioavailability and toxicity of pollutants such as PAHs. Altogether, these findings emphasize the need for improved marine plastic pollution management and reducing environmental pollutant inputs.

Regarding growth and development, investigations on the influence of microplastic (MPs) contaminates have revealed notable consequences on the development of marine zooplankton and other invertebrates. These effects include reduced weight in lugworms (Besseling et al., 2013), intergenerational developmental responses in copepods (Lee et al., 2013), abnormal growth delays in juveniles (Messinetti et al., 2018), and larval development in sea urchins and ascidians,

alterations in development parameters in shellfish (Balbi et al., 2017), as well as the occurrence of malformed or deceased embryos.

Zooplankton are a vital part of the marine food chain, and their death can seriously affect the ecosystem. They are the primary food source for many species of fish and other marine animals. When zooplankton dies due to toxicity co-contaminants of MPs in the ocean, it can lead to a decline in fish populations and other marine animals that depend on them for food. This can have a ripple effect throughout the entire ecosystem (Lindsey at el., 2010)

It is important to address the issue of MPs contaminants pollution in the marine ecosystem by formulating policies and rules and developing alternative eco-friendly materials to replace microplastic. The concentrations of microplastics present in some marine areas and predicted for most oceans in the coming decades can ultimately cause harm to marine habitat-forming species, such as corals.

Microplastics co-existing contaminants are a global environmental concern, and research has shown that they are readily ingested by several zooplankton taxa, with associated negative impacts on biological processes (Botterell et al., 2019) Zooplankton is a crucial part of the marine food chain, and their death due to toxicity co-contaminants of MPs in the ocean can lead to a decline in fish populations and other marine animals that depend on them for food. This can have a ripple effect throughout the entire ecosystem (Lindsey et al., 2010). The concentrations of microplastics present in some marine areas and predicted for most oceans in the coming decades can ultimately cause harm to marine habitat-forming species, such as corals (Botterell et al., 2019)

Although microplastics are abundant and widespread in the marine environment, there is a lack of understanding of the bioavailability and effects of these contaminants on zooplankton. Several

physical and biological factors can influence the bioavailability of microplastics to zooplankton, such as size, shape, age, and seasonality. While there are studies on the ingestion of microplastics by zooplankton, the impact of co-existing organic contaminants on these organisms remains unclear. Further research is needed to understand the interaction between microplastics and organic contaminants and their effects on zooplankton in the ocean. Researchers should investigate the potential for zooplankton grazing on microplastic organic contaminants to have significant regional as well as downstream effects.

4.2. High trophic-level species

Microplastics in the ocean can absorb and transport toxic chemicals such as polychlorinated biphenyls (PCBs) and pesticides, which can harm marine organisms at all levels of the food chain, including the highest trophic-level species. The coexisting contaminants can exacerbate these effects by interacting with microplastics in complex ways.

The toxicity of co-existing contaminants of microplastics, such as persistent organic pollutants (POPs) and heavy metals, may exacerbate these impacts. Studies have shown that these co-existing contaminants can accumulate in the tissues of marine organisms and cause adverse effects on their health and reproduction (Rochman et al., 2013; Andrady, 2011)

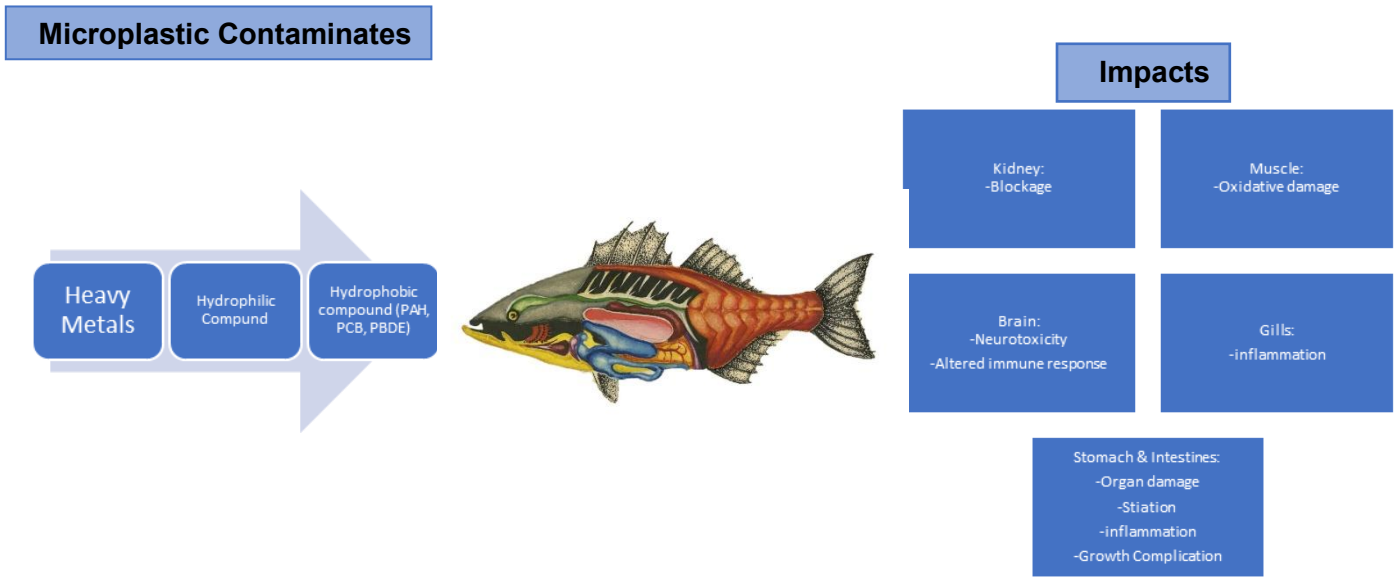

Figure12 . Impacts and combined effects of microplastic co-existing contaminants on Heigh Level species. (Source: Amelia et al., 2021)

Chen et al. (2021) found that the combined exposure to microplastics and cadmium caused oxidative stress and DNA damage in the liver of zebrafish, a standard laboratory model for fish toxicity testing. Another study by Su et al. (2021) reported that combined exposure to microplastics and polycyclic aromatic hydrocarbons (PAHs) led to increased mortality, reduced growth, and altered gene expression in the mussel Mytilus couscous. Researchers found that microplastics can also interact with POPs, such as PAHs, which are known to have negative impacts on marine organisms. When microplastics and POPs co-occur, microplastics can act as a source of these pollutants to marine organisms, potentially leading to adverse effects on the highest trophic-level species (Bakir A et al., 2014).

Microplastics can alter the behavior of marine organisms and feeding patterns, indirectly affecting the highest trophic-level species. For example, a study found that microplastics can alter the scent

of prey, making it less attractive to predators such as fish and marine mammals. This could decrease food availability for these predators and negatively impact their survival, Savoca et al. (2016). The odor of plastic debris in the ocean is attractive to mammals, which rely on odor cues for foraging. Plastic debris could displace the odor of natural prey, leading to changes in foraging behavior. Al-Sid-Cheikh et al. (2020) suggested that the presence of microplastics in the gut of marine organisms may increase the bioavailability and toxicity of POPs, leading to detrimental effects on their growth, reproduction, and immune system.

Zebrafish larvae have been extensively utilized as a model organism for studying zooplankton, mainly due to their heightened sensitivity to contaminants (Yang et al., 2020). Multiple studies have indicated that the combined effects of different substances on zebrafish larvae are more significant than the individual effects. For instance, the presence of plastic particles (PS) intensified the negative impact of methylmercury (MeHg) on the locomotor activity of zebrafish larvae (Danio rerio). This combination also downregulated genes associated with neurotransmitters, such as gfap, ache, and scl1A3b (Zhu et al., 2022). Another study demonstrated that the simultaneous exposure of microplastics (MPs) and copper (Cu) resulted in a synergistic effect on zebrafish larvae, leading to increased mortality and oxidative damage during the period of 2 to 96 hours after fertilization. The observed effects included elevated levels of reactive oxygen species (ROS), catalase (CAT), and glutathione peroxidase (GPx), indicating the induction of oxidative stress and activation of the antioxidant defense system. Additionally, neurotoxicity was observed, along with disruptions in avoidance and social behaviors (Santos et al., 2021). Similarly, the combined exposure of plastic particles (PS) and cadmium (Cd) exacerbated the reduction in body weight of zebrafish during early life stages (Chen et al., 2022).

Studies have also found that MPs act as a conveyor of toxic pollutants (e.g., POPs, PAHs, DDT) (Verla et al., 2019; Wan et al., 2020) and increase the bioaccumulation of sorbed pollutants in aquatic mammals (sharks, whales, etc.) directly and indirectly via the food web. Gut surfactants accelerate the release of hydrophobic organic contaminants from MPs and bioaccumulate them in different tissue. This contrasts with the behavior observed in seawater. The phenomenon, known as "releaser effects," was documented in a study by Lee et al. in 2019. As a result, the accumulation of these organic pollutants in aquatic mammals can have severe detrimental effects on their well-being. These effects include congenital disabilities, disruption of the endocrine system, dysfunction of the immune system, damage to blood vessels, disorders of the nervous system, impaired kidney and gastrointestinal function, and an increased risk of cancer (Nabi et al., 2017). Pesticides, when present in aquatic environments, can contribute to oxidative stress in aquatic mammals. This leads to the production of harmful superoxide molecules and disturbs various liver functions such as detoxification, metabolism, and immunity. Consequently, the levels of reactive oxygen species (ROS) increase in the liver (Chen et al., 2021). As a response to the toxicity, inflammation, degeneration of hepatocytes, mitochondrial dysfunction, and apoptosis occurs in the liver of aquatic mammals (Karami-Mohajeri et al., 2017). If MPs interact with pesticides, they may pose more serious impacts on marine species; understanding their interaction is thus essential.

According to Gallo et al. (2018), recent scientific findings indicate that chemicals linked to microplastics may exhibit endocrine-disrupting properties. These substances are ingested by filter-feeding organisms such as baleen whales through their feeding mechanisms. These substances' endocrine-disrupting properties can potentially affect the control of essential biological functions such as development, reproduction, metabolism, and behavior. Due to their high trophic level in the ocean and the vast amounts of prey they consume, including creatures that may have

accumulated microplastics and other contaminants, baleen whales are particularly at risk to these negative consequences. This discovery underscores the importance of understanding and addressing the impact of microplastic contaminants on the health of marine species, particularly those occupying higher trophic levels in the food chain.

Pesticides are a major type of pollutant in the fish liver. Based on the analysis of Organochlorine pesticides (OCP), the concentration of total DDTs in the liver was found to be two or three times higher. However, the levels of OCPs in the fish muscle showed greater variation among different treatments and sampling periods. Interestingly, the MP index displayed a negative correlation with hexachlorobenzene (HCB) levels and a positive correlation with p,p′ DDT levels in the liver. Furthermore, the levels of pollutants were found to be associated with biological factors such as the overall size and weight of the organisms. These findings indicate that the accumulation of pollutants is influenced by the molecular structure of the chemicals and that microplastics may be linked to the detoxification system (Rios-Fuster and et al, 2021).

Waterbirds, including seabirds, are known to collect food from the ocean, which makes them inevitably susceptible to the harmful effects of microplastics' co-existing contaminants in the ocean (Fossi et al., 2018). The ingestion of plastic by seabirds can also lead to the ingestion of POPs and other harmful chemicals, which can negatively affect their health (Kuepper et al., 2022). Persistent organic pollutants, such as PCBs and organochlorine pesticides can accumulate in the tissues of seabirds, leading to negative effects on their survival, growth and development, reproductive output, and physiology (Bost et al., 2009). Antarctic seabirds can experience the accumulation of microplastic contaminants, including POPs in their tissues due to consuming fish contaminated with such substances, leading to higher concentrations in certain years than others.

This accumulation can lead to negative effects on the health of seabirds, including reproductive failure and mortality (Wilcox et al., 2015)

Microplastics in the ocean pose a significant threat to high tropic species at all levels of the food chain. They can absorb and transport toxic chemicals such as PCBs and pesticides, which can harm marine life. Studies have shown that microplastics can alter marine organisms' behavior and feeding patterns, indirectly affecting higher trophic-level species. Moreover, the combination of microplastics and various organic contaminants can have severe adverse effects on marine organisms, including oxidative stress, DNA damage, neurotoxicity, and disruption of vital biological functions. Aquatic mammals, seabirds, and fish are particularly vulnerable due to their high trophic level and feeding habits. Understanding and addressing the impact of microplastic contaminants on marine species, especially those at higher trophic levels, are crucial for protecting marine ecosystems.

The effects of microplastic co-existing contaminants on the behavior and physiology of higher trophic species, including fish and mammals, are not well understood and require further investigation as their potential impacts on human health and the marine ecosystem.

5.2 Human health

Microplastic contamination in seafood has raised concerns about potential human health risks. Ingestion of contaminated seafood could lead to the accumulation of microplastics and associated contaminants in the human body, potentially leading to adverse health effects. MPs co-contaminants in the ocean, such as heavy metals and persistent organic pollutants (POPs), can also attach to microplastics and be transported into the human body. These microplastics and their co-contaminants enter the human body through various routes, such as ingestion and dermal contact.

These pollutants can have serious health effects, including developmental and reproductive problems, cancer, and damage to the nervous system (Widianarko et al., 2020). Another study by Prata et al. (2020) suggests that inhalation of microplastics and their co-contaminants can cause respiratory problems such as asthma and chronic obstructive pulmonary disease.

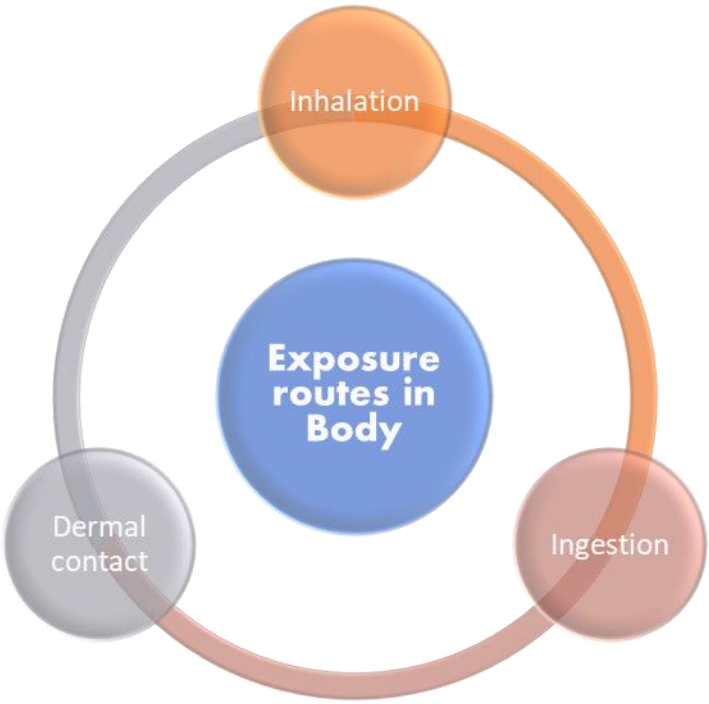

Figure 13. Exposure routes of Microplastic contaminants in the human body.

Additionally, dermal contact with microplastics can cause skin irritation, allergic reactions, and eczema. Heavy metals such as lead, cadmium, and mercury are highly toxic and can cause various health effects, including damage to the nervous system, kidney, and liver. Studies have found that microplastics can absorb heavy metals from the surrounding water and transport them into the bodies of marine organisms, which can then enter the human food chain (Prata et al., 2020).

POPs are a group of highly toxic chemicals that do not break down easily in the environment and can accumulate in the bodies of marine organisms. Microplastics can act as a transport mechanism for POPs, increasing their bioavailability and toxicity. POPs can accumulate in the food chain, significantly negatively affecting human health and the environment. Exposure to POPs through microplastic ingestion can cause hormonal disruption, immune system suppression, and cancer (Jabeen et al., 2018). POPs can also cause developmental and behavioral problems in children. They are organic compounds that are resistant to degradation through chemical, biological, and photolytic processes. However, the extent of the risks to human health from microplastic ingestion is not yet fully understood, and more research is needed to assess the potential impacts. Recent studies have also shown that microplastics may harm human health by ingesting contaminated seafood (Prata et al., 2020). Seafood consumption is a significant pathway through which humans may be exposed to microplastic contamination. In 2015, global seafood intake accounted for 6.7% of total protein consumed and approximately 17% of animal protein consumption (FAO,2016). On a global scale, individuals consume over 20 kg of seafood per year, while in the USA, the average annual consumption is 7 kg (FUS, 2015). The global seafood trade in 2016 amounted to $132.6 billion, with more than 90% of US seafood being imported from regions that experience substantial waste leakage and pelagic plastic pollution (Lusher et al., 2017). About half of the seafood consumed worldwide is obtained through aquaculture, while the other half is obtained from wild-caught sources. Consuming seafood, as well as other types of food, that are contaminated and drinking water that is contaminated are the primary ways through which the gastrointestinal tract can be affected. Consuming whole organisms carries a greater risk compared to consuming those that have been gutted or had their internal organs removed (Carbery et al., 2018).

These contaminants can enter the food chain and ultimately end up in the human diet, posing a significant risk to food safety and human health. This is a crucial pathway for exposure to microplastic contamination (Carbery et al., 2018; Zhang et al., 2020a; Cox et al., 2019).

Long-term consumption of water containing elevated levels of phthalate, a chemical commonly present in plastics, has been linked to adverse liver and reproductive outcomes in individuals. The US Environmental Protection Agency (USEPA) has set a safety threshold of less than 6 µg/L for this chemical in drinking water. This information comes from research conducted by Lambert et al. (2014), Martin and Voulvoulis (2009), and the USEPA (2012). Other health-threatening plastic additives, like monomers, initiators, catalysts, emulsifiers, and stabilizers, can pose serious health risks. Some examples of these chemicals are styrene, benzoyl peroxide, zeolites, and azobisisobutyronitrile, as identified by Todd et al. (2003). In addition, microplastics in the ocean absorb carcinogenic polycyclic aromatic hydrocarbons (PAHs) and other environmental contaminants. These chemicals accumulate in the fatty tissues of animals that humans consume as food, as highlighted by Hwang et al. (2020).

Endocrine-disrupting chemicals (EDCs) such as phthalates, bisphenol A, flame retardants, and perfluorinated chemicals released into the seas can disrupt endocrine signaling, reduce male fertility, damage the nervous system, and increase cancer risk if they directly or indirectly enter the human body (Landrigan PJ, et al. 2020) (give original refs). Exposure to these EDCs can cause bilateral cryptorchidism, which is associated with a greater risk of azoospermia, poor semen quality, increased risk of testicular cancer, and reduced paternal fertility rates. Furthermore, the negative impact of organic contaminants such as Methylmercury and PCBs on human health is well-known (Miller fj et al., 2009). For instance, Methylmercury harms the development of the brains of fetuses if their mothers consume contaminated seafood during pregnancy, resulting in

reduced IQ and increased risk of autism, ADHD, and learning disorders in children (WHO, 2017). However, the impacts of MPs and EDC co-existing contaminants on human health are barely studied, which is worth investigating to expand our knowledge of the potential risks to humans when exposed to EDC and MPs.

In conclusion, microplastics and their co-contaminants in the ocean can significantly affect human health. Therefore, it is essential to reduce the production and usage of single-use plastics and to properly dispose of plastic waste to prevent further contamination of the environment. The combination of MPs and their adsorbed chemicals can be more toxic than either counterpart on its own (Jiang et al., 2020). The interaction modes of MPs and various contaminants on various biomarkers are difficult to clarify at this stage due to the limitation of available data, and more future studies are needed (Arienzo et al., 2021). The complex toxic interaction highlights the generality and specificity of the influence of MPs on the toxicity of co-contaminants, which is particularly important for the risk assessment of MPs with specific contaminants.

5. Conclusions and Recommendations

Based on the final project report A and B, we made a review of MPs distribution in the marine environment. The research presented in this study demonstrates the significant influence of various environmental factors on the fate and transport of MPs and co-existing organic contaminants in aquatic and terrestrial ecosystems. The visual association between the offshore limit of debris concentrations and the bottom salinity front in both ecosystems highlights the importance of salinity in governing the distribution of MPs. Marine microplastics primarily originate from larger plastic waste left on land, highlighting the need to address plastic pollution at its source. Moreover, the ability of MPs to absorb water pollutants, including persistent organics and metals, further

emphasizes their potential role as carriers of contaminants in the environment. Salinity, pH, temperature, suspended particles, and MP weathering have diverse effects on the sorption and behavior of MPs and co-contaminants. Salinity influences the geographic distribution of MPs in river estuaries and impacts their sorption behavior. Higher salinity levels have been associated with increased MP abundance, as seen in various studies. However, the effects of salinity on sorption can vary depending on pH levels and the type of organic contaminants.

Temperature plays a crucial role in the interaction between MPs and co-existing organic contaminants. It affects the adsorption and sorption capacities of both pollutants, with some substances showing increased sorption at higher temperatures while others exhibit the opposite trend. The presence of suspended particles in the water column significantly influences the fate and behavior of MPs and co-contaminants. MPs can adsorb organic pollutants onto their surfaces, leading to potential secondary contamination sources. The interactions between suspended particles and contaminants can further affect their sinking behavior and bioavailability. pH is another critical factor that impacts the sorption of MPs and co-contaminants. The pH level of the surrounding water can influence the protonation of the MPs' surface and the sorption affinity of different organic contaminants. MP weathering alters the physical and chemical properties of MPs, affecting their sorption capabilities and interactions with co-existing contaminants. The surface modifications due to weathering, such as increased hydrophilicity and oxygen functional groups, can enhance the sorption of both hydrophilic organic contaminants and metals.

On the other hand, MPs are significant carriers of organic and inorganic pollutants in the ocean. They can accumulate POPs such as PCBs, PAHs, and organochlorine pesticides like DDT or HCB from the water. These toxic chemicals can contaminate marine biota when ingested, and the

biomagnification of MPs and their co-contaminants can have far-reaching consequences on marine ecosystems and human health. Phytoplankton, as primary producers of the ocean, play a critical role in marine ecosystems by generating organic matter and oxygen through photosynthesis. MPs and their co-contaminants can interfere with phytoplankton's ability to feed, carry out photosynthesis, and grow, affecting their reproduction and overall community dynamics. This disruption can have cascading effects on the entire marine food chain and the sustainability of aquatic ecosystems. Zooplankton, as primary consumers of phytoplankton, are also impacted by MPs and co-contaminants, leading to reduced survival, growth, and reproductive success. As key players in nutrient recycling and carbon sequestration, their decline can disrupt marine ecosystems' functioning and carbon cycling, affecting atmospheric CO_2 levels and climate change. At higher trophic levels, marine organisms such as fish, marine mammals, and seabirds can be exposed to MPs and their co-contaminants through their diet, leading to harmful effects on their health, development, and reproduction. The interaction of MPs with other contaminants can amplify their toxicity, making the situation even more concerning. The presence of MPs and their co-contaminants in the ocean poses potential risks to human health, primarily through the consumption of contaminated seafood. Ingestion, inhalation, and dermal contact with MPs can lead to the accumulation of toxic chemicals in the human body, causing various health issues, including developmental problems, cancer, and damage to the nervous and immune systems. To address these challenges, it is crucial to take immediate actions to reduce plastic pollution and prevent the release of MPs into the environment. This requires implementing strict regulations on plastic production, usage, and waste management, as well as promoting sustainable alternatives to single-use plastics. Additionally, more research is needed to better understand the interactions

between MPs and co-contaminants, as well as their long-term effects on marine ecosystems and human health.

Based on our research, first, we strongly recommend reducing the use of plastic products and improving waste management. Second, monitoring and regulating organic pollutants contamination in waterways. Finally, reducing plastic usage, proper disposal of plastic waste, and increase awareness, research, and innovation. In addition, there is a huge knowledge gap between the organic NPs and MPs interaction, which could be attractive for researchers.

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