Archives of Environmental Protection PL ISSN 2083-4772
Vol. 50 no. 3 pp. 26–35 DOI:10.24425/aep.2024.151683

An overview – Fate and analysis of marine microplastics with insights into microfluidics, biofilms, and future ecological threats.

Mahima Ganguly[1], Jithu Valiamparampil[1], Divyashree Somashekara[2], Lavanya Mulky[1]*

[1]Department of Chemical Engineering, Manipal Institute of Technology, Manipal Academy of Higher Education, Manipal, 576104, India
[2]Department of Biotechnology, Manipal Institute of Technology, Manipal Academy of Higher Education, Manipal, 576104, India

* Corresponding author's e-mail: lavanya.m@manipal.edu

Keywords: pollution, microplastic, biofilms, microfluidics, sampling

Abstract: Pollution associated with microplastics (MP) over time is becoming a genuine cause of concern because these micro-sized plastics possess the ability to accumulate toxic contaminants of diverse types. Their propensity to absorb or adsorb pollutants from the surroundings increases the toxicity of microplastics. Multiple root causes lead to the accumulation of microplastics in aqueous ecosystems, necessitating specialized techniques for investigating, handling, and disposing of them. This overview elaborates on the several modes of degradation of microplastics in aquatic systems. It further provides insights into the novel 'Microfluidics' technique for detecting microplastics in marine environments. Additionally, as a rising hope for the degradation of microplastics through biofilm formation, distinct types of bacteria found in marine habitats are discussed in this paper. Finally, this review elucidates the problems associated with microplastic pollution in aquatic ecosystems and explores methods for their safe disposal in the future.

Introduction

The first advanced plastic, Bakelite, was created in 1907. Since then, numerous cost-effective procedures have been developed for the mass production of abundant plastic polymers, which are used in various day-to-day applications. Plastics possess desirable properties such as long durability, resistance to corrosion, non-reactivity with materials, and low cost, which make them one of the most highly demanded products in the world. In 2009, it was noted that about 230 million tonnes of plastic were produced globally, accounting for approximately 8% of global oil production (Verma et al. 2016).

Plastics, after being discarded, take a significantly longer time to decompose or degrade, causing threats to ecology and environmental contamination. As a result of recent responsiveness and global concern, attempts are being made to reduce, reuse, and recycle the plastics that are used. Although these efforts seem to be succeeding for a fraction of disposed plastics, the remaining waste either goes into landfills or enters water ecosystems via multiple pathways (Lange 2021). The formation of microplastics and nanoplastics arises from the breakdown of larger plastic fragments through diverse physical, chemical, and biological processes. Plastics can decompose or degrade through a range of mechanisms, including biotic (caused by the activity of living organisms), abiotic (resulting from non-living processes), photodegradation (caused by exposure to light), thermal (induced by heat), and mechanical means (resulting from physical forces) (Dimassi et al. 2022) it takes into account the leachability of the various chemical substances (additives. In recent decades, environmental researchers have been motivated to explore micro-sized contaminants, their effects, and their fate in marine, terrestrial, and atmospheric ecosystems. Recently, microplastics, consisting of minute fragments, plastic granules, and fibers, have been classified as pollutants. The sizes of these micro-pollutants range from 1mm to 10 mm, but various researchers have attempted to classify them differently, such as less than 1mm, 2mm, or 2 to 6mm (Abdel-Aziz 2014a). The lack of clarity in terms of size and categorization presents a significant challenge when attempting to examine and analyze the available data using various established scientific parameters (Oberbeckmann et al. 2015).

This paper aims to first understand the sources and transport pathways of microplastics into aquatic ecosystems such as lakes, rivers, estuaries, seas, and oceans. Once these waterways are contaminated, it is crucial to separate microplastics from other pollutants for further detection and analysis. This paper will address this issue by highlighting "Microfluidics" – a novel technique for the detection of microplastics. This paper also focuses on the biological degradation of microplastics via biofilm formation caused by characteristic microorganisms in water bodies. The types of marine bacteria and the mechanism of biofilm formation will be discussed in detail. Additionally, it is important to examine the drawbacks associated with microplastic contamination and explore solutions for improving living standards and achieving a healthier environmental equilibrium. Therefore, this paper will suggest effective strategies to minimize microplastic contamination and control existing pollution conditions.

Microplastic degradation in aquatic ecosystems

Microplastic contamination can occur in both groundwater and surface water sources, making it a complicated and tedious task to trace their origin and transport mechanisms in our environment. This complexity arises because little is understood about the methods that control their transmissions within aquatic habitats. Some of the primary factors affecting their distribution and transport include the inherent physical and chemical properties, such as shape, size, density, chemical structure, and composition. Plastics are used in a diverse array of applications, and their decomposition mechanisms and subsequent pathways of transport in aquatic environments exhibit considerable variation. Moreover, there are limited methods to trace the origins and distribution of microplastics, as plastic handling and disposal protocols vary across different regions of the world. Naturally, higher amounts of plastics are used in heavily inhabited metropolitan areas, leading to more traces of microplastics observed there.

As mentioned earlier, the process of microplastic degradation can occur primarily through various abiotic and biotic mechanisms, a schematic representation of which is given in Fig 1. Numerous researchers have investigated the decomposition and breakdown of plastics to comprehend the underlying mechanisms and modifications in polymer properties over time. The subsequent paragraphs will provide a comprehensive elucidation of the major pathways of degradation.

Abiotic degradation of microplastics

Microplastics are generally non-biodegradable in nature, as structurally plastics are complex polymers that take a lot of time to degrade naturally in the environment (Klein et al. 2018) so-called microplastics (particle size, 1–5,000 μm. Abiotic degradation usually refers to the degradation of plastic fragments under the influence of temperature, sunlight, mechanical forces, etc. The most common methods of mechanical and photodegradation are described in the following subtopics.

Mechanical degradation of microplastics

The mechanical breakdown of microplastics represents a prevailing form of degradation. This phenomenon is of utmost significance in the formation of minute plastic particles through the physical abrasion of plastic particles in aquatic environments (Corcoran 2021). The process of mechanical abrasion causes microplastics to break down into smaller fragments, and repeated abrasion can further smooth out their edges. This rounding effect is attributable to the physical characteristics of both the plastic material and the abrasive surface, as well as the duration and intensity of the abrasion process. The resulting microplastic particles with rounded edges can have significant consequences for their environmental destiny and behavior. For instance, they can be more readily transported by water or wind currents and more easily ingested by aquatic organisms. Additionally, the similarity of their morphology to natural sediment grains can make it difficult to distinguish them from natural particles, presenting a challenge for accurately quantifying their prevalence and distribution in the environment (Bremerstein et al. 2015, Mekaru 2020).

Photodegradation of microplastics

Photochemical degradation is a process that breaks down microplastics, resulting in the release of polymeric fragments,

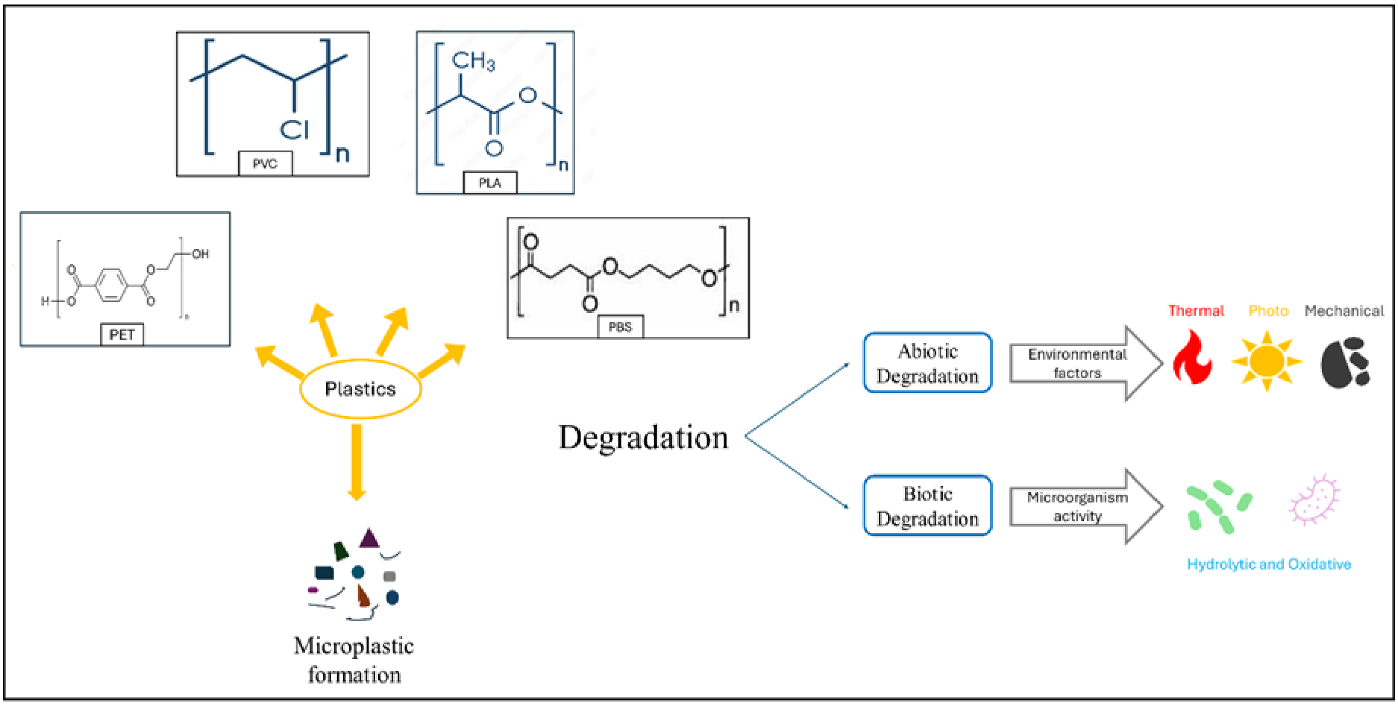

Figure 1. Different mechanisms of degradation of microplastics.

by-products, and chemical additives. This process involves the exposure of plastic particles to sunlight, which causes the polymer chains that make up the plastic to break down (Chen et al. 2019). Given the ubiquitous presence of microplastics and organic pollutants in natural water systems, it is likely that the photodegradation and other environmental transformations of organic micropollutants will be influenced by their adsorption onto microplastics, which may sink to subsurface sediment. Additionally, certain microplastics, such as polystyrene (PS), phenol-formaldehyde (PF), and polyethylene (PE), can absorb light energy and generate reactive radicals and/or free electrons (Zhu et al. 2019).

This interplay between microplastics and organic pollutants has significant implications for environmental and public health. It can exacerbate the persistence and toxicity of these pollutants in aquatic ecosystems. The generation of reactive radicals and free electrons by certain types of microplastics can further contribute to the degradation of organic pollutants and the formation of new, potentially harmful compounds (Osman et al. 2023). The impact of microplastics on the fate and behavior of organic pollutants in natural water systems is an active area of research. Further studies are needed to elucidate the complex interactions between microplastics and organic pollutants in aquatic environments.

Biotic degradation of microplastics

Conventional plastics are typically characterized by an extremely low bioavailability, as only a small fraction of the polymer is exposed to potential degraders due to their solid nature. Moreover, microorganisms cannot directly use macromolecule polymers; they require extracellular enzymes to break them down into smaller molecules that can be absorbed and metabolized by the cells (Battin et al. 2016). The limited bioavailability is a major factor contributing to the persistence of conventional plastics in the environment, as it restricts the ability of microorganisms to degrade them. This persistence can have significant negative impacts on the environment and human health, leading to the accumulation of plastic debris in both aquatic and terrestrial ecosystems (Zhang et al. 2021). Microbial degradation can occur under both aerobic and anaerobic conditions, depending upon the surrounding conditions and the chemical structure of microplastics (Zhang et al. 2021). The different types of microorganisms involved in the degradation of microplastics through biofilm formation in aquatic environments will be discussed in future subtopics.

Microfluidics: A novel detection technique of microplastics

Among the various organic and inorganic pollutants present in marine ecosystems, it is crucial to separate microplastics from other contaminants. Traditionally, methods such as visual sorting and scanning electron microscopy (SEM) are used for sampling and detecting microplastics, as schematically described in Fig 2. Microfluidics is emerging as a sophisticated technology that enables high-speed, high-throughput, low-cost analysis, and high sensitivity by modifying fluids using microfabricated channel and chamber structures. Additionally, microfluidics can create a well-controlled microenvironment for fluid and particle manipulation (Farré and Barceló 2020). It is also being used in advanced chemical/biological analyses, as well as low-cost point-of-care tests, with unconventional processes appearing at the micrometer scale (Zhang et al. 2022). The surface characteristics of the device material are enhanced, which can result in unique functionalities or challenges not encountered at the macroscale. Furthermore, each material is inherently linked to specific microfabrication processes and device features. As a result, the choice of material used to make the device is crucial in microfluidic technology (Ren et al. 2013).

Chip-scale sorting, concentration, and spectroscopic analysis principle

The ample supply of the tiniest microplastic particles, sized between 1μm to 100μm, is one inspiration for conducting research in microfluidics, which particularly targets this category of particles. Microfluidics helps propose a productive methodology for their convenient quantification and identification, recognizing the type of plastic particles and determining if they might be non-plastic. The intention of these studies is to accomplish two tasks with high throughput (Regnault et al. 2018): a) to enable detailed, large-scale studies on aquatic microplastics and b) to drastically reduce the time required for analysis, which is a key factor in monitoring (Elsayed et al. 2021).

It is worth mentioning that the maximal particle dimensions analyzed using microfluidic techniques can go up to a few hundred microns or 1 mm and are not only limited to 100 μm. The suggested micro-optofluidic platform includes a microfluidic chip designed to perform a variety of activities, such as particle sorting and trapping in specialized ultra-compact on-chip reservoirs (Choi et al. 2015). This allows for rapid spectroscopic examination and imaging of the particles, as well as flow cytometry, which serves as an effective reference method for the size distribution of particles. The chips are assessed using modeled plastic particles with known sizes and properties, diluted in ultra-pure water at specified proportions (Mark et al. 2010).

To substantiate and prove this concept, several demonstration projects were conducted in which particles of varying sizes were sorted and trapped in compartmentalized dedicated reservoirs, then imaged and evaluated using various spectroscopic methods such as a Raman microscope, a Raman spectrometer, and an FTIR microscope. The results obtained from these experiments were compared (Wellner 2013). The chip design includes reservoirs with lateral dimensions ranging from about 100 to 300 μm, allowing the concentration of all trapped particles in such a tiny sub-millimeter space, compared to centimeter-scale filters, which is critical for any further rapid spectroscopic analysis of the sorted particles. Furthermore, the chip reservoirs can be configured to handle particles of varying sizes (Pattanayak et al. 2021). These ultra-compact reservoirs are a significant advantage over traditional procedures that use centimeter-scale filters, which require enormous time to scan the entire surface. As a result, this approach is intended to be time-efficient and low-cost. Microfluidics provides precise readings and facilitates the coupling of optical beams for spectroscopic investigation. (Elsayed et al. 2021).

Flow cytometry measurements

Flow cytometers are capable of providing precise information regarding particle shapes, sizes, and counts, along with other physical and chemical properties (Shrirao et al. 2018). Some advanced flow cytometers are equipped with high-speed cameras and a light source that can capture as many as thousands of images per second, providing detailed and crucial information about the particles in the sample used for analysis. Specialized machine-learning techniques developed for this application can be used to calculate the sizes of particles from the images obtained (Luo et al. 2020). Using image analysis, individual particle images that are successfully captured can be classified into populations of various sizes (Mauk et al. 2013). This classification procedure can accommodate particles up to a few hundred microns in size, making it quite flexible. Other variables, such as the aspect ratio of particles, can also be used to categorize particles into distinct clusters, allowing the categorization of particles of various forms, including fibers (Konry et al. 2012). It is worth noting that flow cytometry has already been used in water analysis for counting and classifying microparticles using deep learning and image processing technologies (Sgier et al. 2016).

Trapping of microplastic particles and sorting on-chip

The suggested microfluidic chips can perform at least two functions: one is to classify the particles into separate reservoirs based on their size, and the other is to trap microplastic particles in specific on-chip reservoirs. The chips are evaluated by inserting a solution of ultra-pure de-ionized water containing standard spherical plastic particles into the chips, and photographs of the trapped particles are acquired for the reservoirs. A technology called Pinched Flow Fractionation (PFF) is used for sorting the particles (Lu and Xuan 2015).

Microfluidic chips provide a novel approach to investigating the toxic effects of MPs, offering an alternative to conventional techniques for separation and detection. However, the use of microfluidic systems may have limitations in terms of sensitivity and specificity, depending on the incorporated modules, such as sensors. Despite these limitations, microfluidic systems offer advantages in the separation of various substances, including MPs, pathogenic bacteria, algae, fungi, rare metals, and proteins, all of which have a direct impact on the analysis of MPs. Thus, microfluidic chips are a promising tool for examining MPs and other substances in a range of applications.

A rising hope of plastic degradation with marine bacteria

It is a known fact that a major part of our earth is covered in a cold climate with temperatures below 50ºC. About 70% of the earth is covered by water bodies like the deep sea, some of which are found at a constant temperature of 20ºC. Interestingly, bacteria have been found to accommodate themselves in every possible condition, from the coldest temperatures to the hottest places, and even in environments where the presence of air and sunlight is almost nil (Russell 1990). These resilient bacteria have unique characteristics due to their habitation in rare conditions, including the ability to break down plastic waste, which has attracted researchers (Romera-Castillo et al. 2018)

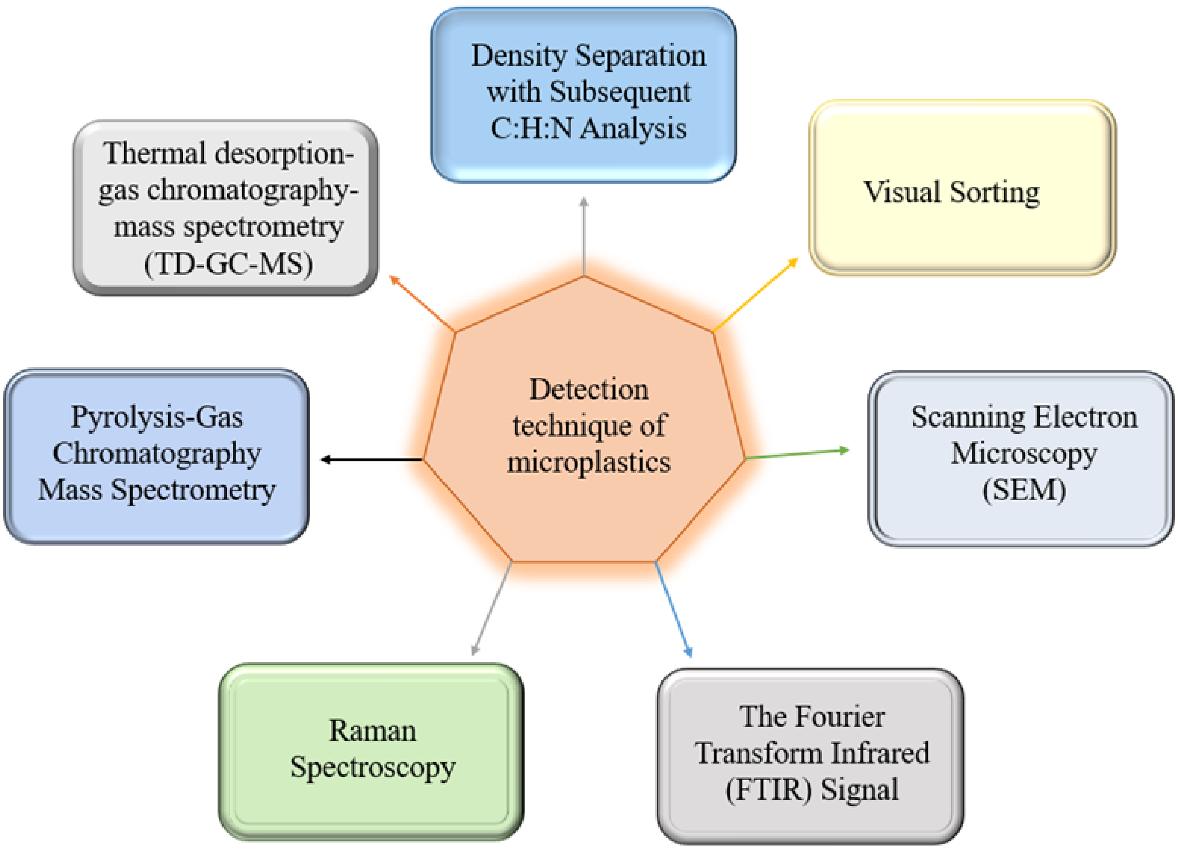

Figure 2. Methods for detection and quantification of microplastics.

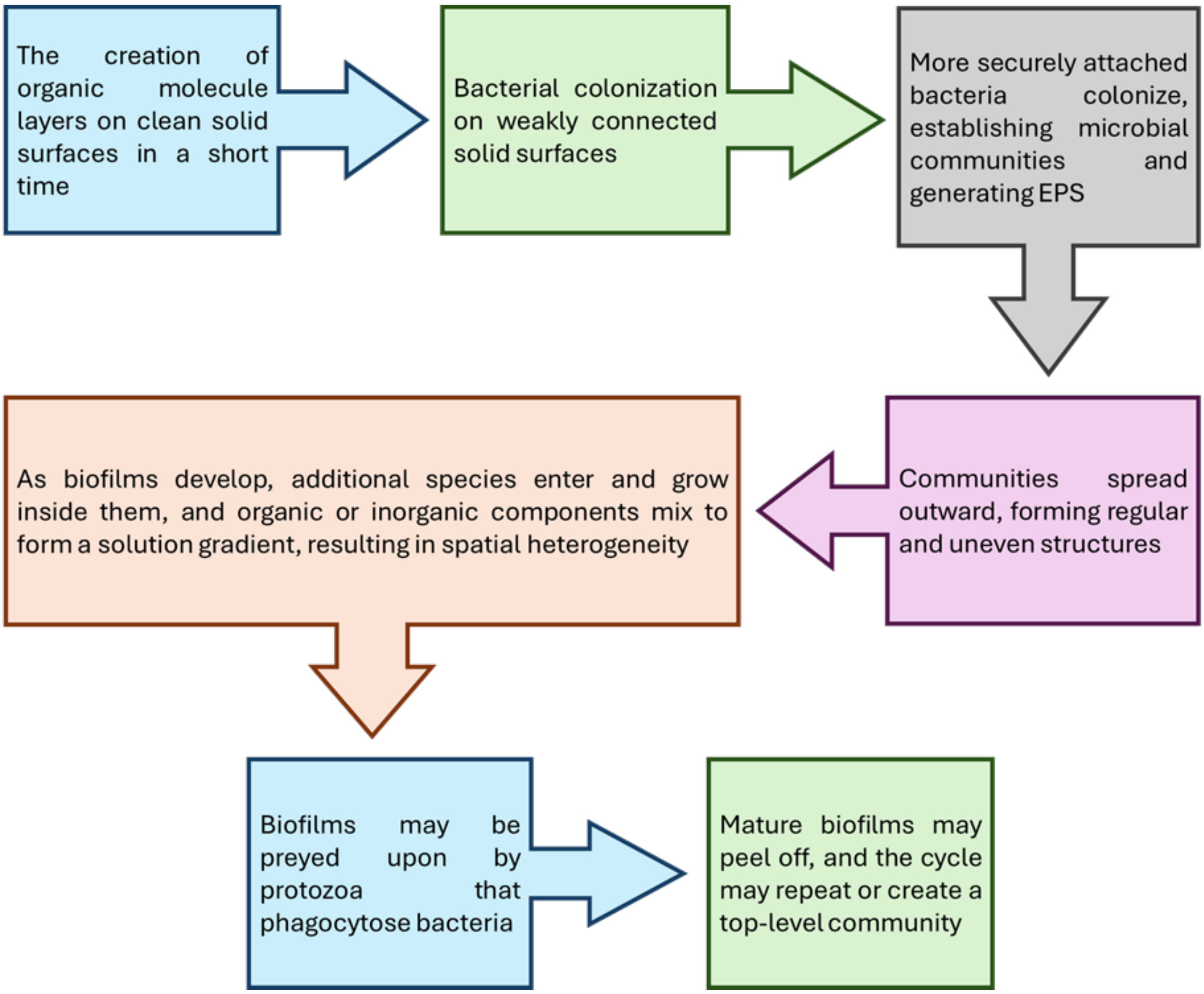

Figure 3 . Breakdown of the traditional biofilm development process.

however, remains unknown. Here we show that plastics release dissolved organic carbon (DOC. As the amount of plastic debris disposed into the ocean increases, studies have shown that plastic can provide dissolved carbon into the oceans, acting as a substrate for benthic organisms and stimulating heterotrophic activities by microorganisms (Pauli et al. 2017). Adapting to this newly dissolved carbon substrate, bacteria may develop new characteristics, including the production of cryogenic enzymes. The distinctive abilities of microorganisms to adapt to low temperatures provide enormous opportunities for researchers and engineers working in the field of plastic waste management.

From diverse strains isolated from various species in the Arctic Sea in the Canada Basin, some were found to produce lipase. Microorganisms from the genera *Shewanella*, *Pseudomonas*, *Colwellia,* and *Marinomonas* were confirmed to display lipase activity. Of these, 20-40% of psychrophilic strains and 10-30% of psychrotolerant strains exhibited lipase activity even at temperatures as low as 0^0C (Yu et al. 2009). Since some lipases can hydrolyze polyesters like PCL, bacterial strains with lipase activity and the ability to adapt to cold temperatures are important for the biodegradation process. It is possible that other enzymes secreted by cold climate bacteria, such as depolymerases, may also have the ability to degrade plastic (Tokiwa and Calabia 2004). Enhancing this process with additives affecting thermal stability and the capacity to absorb UV rays can further improve the microbes' ability to degrade plastic. Bacteria capable of surviving at low temperatures, such as -10^0C, can be attached to plastic using chemically sensitive polymers. These bacteria have been observed to release protease in excess, showing the ability to produce large amounts of enzymes in polar conditions (Huston et al. 2000). This opens the field for researchers to explore and further study the opportunities hidden under the ice beds.

Biofilm Formation

Biofilms are defined by the International Union of Pure and Applied Chemistry (IUPAC) as an aggregation of micro-organisms where cells cling to each other and/or to a surface, typically buried inside a self-generated matrix of extracellular polymeric substances (EPSs). Biofilms may form on both living and non-living surfaces and can be found in both aquatic and tellurian habitats. Various microscopic organisms such as protists, algae, fungi, and bacteria can easily occupy microplastic surfaces due to the large specific surface area. Biofilm formation is regarded as an essential virulence factor. The creation and growth of biofilms on microplastic surfaces can alter the shape and physical and chemical characteristics of microplastics. This results in a variety of consequences, including vertical mobility, biodegradation, co-migration with chemical contaminants and pathogens, and weathering (Tu et al. 2020).

Primary Stages of Formation of Biofilm

The bacterial release of Extracellular Polymeric Substances (EPS), containing proteins, glycoproteins, and glycolipids, forms a matrix surrounding the bacteria, allowing them to connect to a range of abiotic and biological surfaces (Keswani et al. 2016). Various researchers categorize biofilm development into phases based on core flora and time series. Biofilm development is classified into three stages: the preliminary stage, lasting for about 1 to 14 weeks, the intermediary stage, lasting for about 14 to 35 weeks, and the final stage, lasting about 35 to 45 weeks, depending on alterations in the core flora of the biofilm on the surface of plastic particles exposed at the harbor's bottom. The mechanism of biofilm growth on the surface of plastic flakes in the aquatic ecosystem is well-established (De Tender et al. 2017). WT Wimpenny presented a brief breakdown of the traditional biofilm development process, as demonstrated in Fig. 3 (Wimpenny 1996):

Lennox categorized biofilm development into five steps, as illustrated in Fig 4 (Abdel-Aziz & A, 2014b):

Other scientists have categorized biofilm development into 4 primary stages: (1) adsorption of dissolved organic molecules (2) grouping of prokaryotes, (3) colonization by single-cell eukaryotes, and (4) colonization or grouping of invertebrate larvae and algal spores. These 4 processes might occur concurrently or independently on the surface of microplastics (Wang et al. 2019).

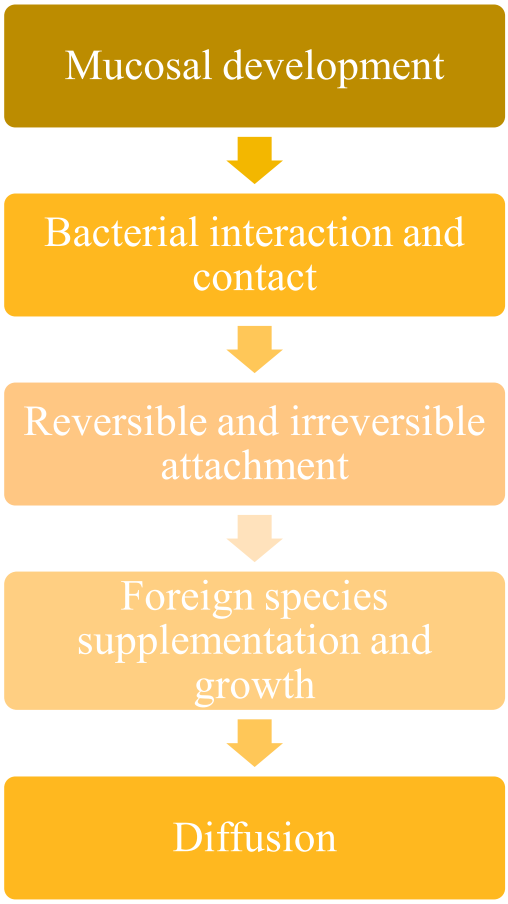

Figure 4. Biofilm development into five steps.

Factors Affecting Biofilm Formation on Microplastics

Firstly, the interaction between the surface of the plastic and the biofilm in the surrounding water takes place. After a few minutes, an adsorption layer of organic and inorganic components forms. Through attractive or repulsive interactions between the external walls of cells and the media surfaces, microorganisms come into contact with the surface. The preliminary conditioning layer might be able to influence colony formation by modifying material-specific surface features (Rummel et al. 2017). Biofilm production is a multistage process influenced by several parameters such as surface characteristics, nutritive compound mixtures, weather conditions, and pH (Sauer 2003). The conditions surrounding the matrix and cell development circumstances (such as climate, carbon supply, liquid media movement, nutritional media ingredients, and maturation characteristics) are complex factors that influence bacterial adhesion to MP surfaces (Renner and Weibel 2011). Various attachment mechanisms between bacteria and matrices promote adherence to the substrate surface through flagella, bristles, pili, and EPS production adaptation. The colonizer and initial conditioning layer modify the material's surface qualities and stimulate the colonization of additional species (Haiko and Westerlund-Wikström 2013). Based on the surface's hydrophilicity or hydrophobicity, electric charge, roughness, and functional groups, microbial cells can adhere to the surface in both general and specific ways (Rosenberg et al. 1982). The chemical characteristics of the conditioning layers are connected to the hydrophobicity or roughness of the preliminary surface of the matrix surface and are critical for biological sedimentation, emphasizing the significance of the fundamental process of adsorption (Lorite et al. 2011). Hook and his team proposed in their research that surface hydrophobicity and polymer shape have little effect on bacterial adherence to polymers (Hook et al. 2012).

Pollutants connected with plastics and their transportation via biofilms

Biofilms may influence the transfer of hydrophobic organic pollutants (HOCs) between plastic debris and water due to their ability to metabolize HOCs along with their sorptive properties (Headley et al. 1998, Paterson and Alexander 1971). Along with additives from newly released plastic waste, highly persistent pollutants can be acquired by plastic from its local surroundings and transported and released by plastic throughout its time in the sea (Teuten et al. 2016, Bakir et al. 2012). To assess the risks associated with microplastics, it is critical to understand the capacity of synthetic polymers to sorb HOCs. Thus, we must consider whether biofilms will influence thermodynamic and kinetic processes. Moreover, EPS forms a rich biological matrix containing proteins, humic acids, polysaccharides, and lipids, which can enhance the sorptive ability of biofilm-coated MP and hetero aggregates (Flemming and Wingender 2010). A wide variety of bacteria, fungi, and algae can degrade HOCs, making them useful for bioremediation of surface waters in situ or as engineered bioreactors (Wu et al. 2014). This illustrates the importance of biofilms in the accumulation and/or removal of plastic-associated chemicals through metabolization, which may affect their bioavailability to consumers ingesting MP (Writer et al. 2011). The introduction of antimicrobial compounds into polymer materials to restrict microbial settlement may cause concern, as these chemicals can leak and contribute to the increase in resistance adaptations in microbial populations (Demeter et al. 2017). It can be concluded that, due to larger surface-to-volume ratios, sorptive mechanisms may result in quicker chemical absorption and release in microplastics compared to macro-plastic litter. Additionally, microbial colonization is promoted by the expanded and eroded surfaces available for colony formation, which might alter the kinetics and persistence of HOCs (Oberbeckmann et al. 2015). These bi-directional relationships, which can influence the kinetics of contaminant uptake and release into and out of the polymeric bulk phase via the active microbial interface, need further study to predict more accurately the hazards posed by microplastics as sources of HOC emission and transport in aquatic environments (Rummel et al. 2017).

Future Prospective

The trade-offs associated with microplastics are a global cause for concern. With the recent increase in awareness, there is now more scope for scientists worldwide to work on this issue. Current reviews help show a way forward in this area (Vaid et al. 2021). The two primary targets can be listed as: (a) analysis of microplastic contamination, with a particular focus on the presence, origins, and fate of microplastics in riverine systems, and (b) understanding and assessing microplastics-related toxicity in aquatic habitats, as well as a critical study of the problems and potential solutions for remediating microplastic contamination in these systems (Chaukura et al. 2021). Even though microbes may colonize any plastic introduced into the water ecosystem, few investigations have been conducted on the interactions between marine microbiota and plastics. As a result, more studies are needed to better understand the interactions between microplastics and microorganisms (Qiu et al. 2022). Humans are at serious risk of microplastic exposure and related illnesses; various scientists have observed microplastic consumption through everyday staples in their research (Lee et al. 2021, Kiran et al. 2022). Some researchers have proved that microplastic contamination via food can lead to serious health concerns, such as endocrine disruption, cancer, inflammation, and, in some cases, fatality (Barboza et al. 2018). Thus, considering the numerous prevailing and emerging hazards related to microplastics, managing them as an evolving pollutant before they become a permanent threat to humans and the environment is crucial (Yong et al. 2020). The amount of microplastics increases considerably as their size decreases (Isobe et al. 2015). According to reported studies, the average size of microplastics depends on the various sizes of the microplastics analyzed after sampling. There is a significant ongoing demand for research to describe the dynamics related to the atmospheric transport of microplastics. Thus, atmospheric particle transport modeling is an essential area of focus for future research (Zhang et al. 2020). Any correlations or links associated with the composition of atmospheric, terrestrial, and marine microplastics have not yet been given careful attention. Additionally, well-grounded research has not yet been conducted to provide sufficient evidence related to source pathways and interlinkages between freshwater, atmospheric, and terrestrial microplastics. The impact of airborne microplastics, their constituent chemical components, and the contaminants they adsorb on ecological and human health is unknown. However, the potential of nano and microplastics to affect this is a cause for concern (Wright and Kelly 2017).

Though a few investigations are currently being conducted to study the sorption, toxicity, and aggregation of pollutants on microplastics in the atmosphere, significant additional research is required to fully comprehend the depth of this problem. Additionally, the interactions of microplastics with other organic toxic compounds and metals in the environment, as well as their effects on and interactions with the environment, humans, and ecosystem health, have received little attention and require further investigation (Wang et al. 2020).

Conclusion

It is commonly assumed that ocean waters serve as a major sink for microplastics, with marine and terrestrial habitats acting as significant sources and pathways for microplastics to reach the sea. In the oceans, plastic contamination primarily occurs due to the presence of large quantities of improperly managed solid waste in terrestrial environments. These wastes are typically transported through wastewater outflows, inland waterways, tidal currents, or wind advection, with rivers playing a particularly critical role. Marine ecosystems are regarded as the ultimate sinks for all plastic trash, including microplastics. Terrestrial, freshwater, oceanic, and now atmospheric habitats are understood to be interconnected through a complex network of source-pathway-sink interactions that impact the flow and accumulation of microplastics in such environmental compartments. This movement significantly influences the source-sink dynamics related to plastic pollution across various ecosystems, including the transfer between aquatic and terrestrial systems. Due to the serious and potentially life-threatening health concerns associated with microplastic contamination, it is crucial to regulate unregulated discharge into waterways. Effective regulation involves addressing the multiple sources and sinks of microplastic particles. Control measures should include promoting sustainable and biodegradable or environmentally friendly alternatives, implementing effective legislation, advancing treatment technologies for microplastics, and upgrading or improving existing wastewater treatment technologies. These actions can contribute to more efficient management of microplastic pollution and prevent leakages.

Conflict of Interest

None

Funding

None

References

Abdel-Aziz, S. M. & A, A. (2014b). Bacterial Biofilm: Dispersal and Inhibition Strategies. Scholarena *Journal of Biotechnology*, 1(1). DOI:10.18875/2375-6713.1.105

Bakir, A., Rowland, S. J. & Thompson, R. C. (2012). Competitive sorption of persistent organic pollutants onto microplastics in the marine environment. *Marine Pollution Bulletin*, 64(12), pp. 2782–2789. DOI:10.1016/J.MARPOLBUL.2012.09.010

Barboza, L. G. A., Dick Vethaak, A., Lavorante, B. R. B. O., Lundebye, A. K. & Guilhermino, L. (2018). Marine microplastic debris: An emerging issue for food security, food safety and human health. *Marine Pollution Bulletin*, 133(May), pp. 336–348. DOI:10.1016/j.marpolbul.2018.05.047

Battin, T. J., Besemer, K., Bengtsson, M. M., Romani, A. M. & Packmann, A. I. (2016). The ecology and biogeochemistry of stream biofilms. [in] *Nature Reviews Microbiology* (Vol. 14, Issue 4, pp. 251–263). Nature Publishing Group. DOI:10.1038/nrmicro.2016.15

Bremerstein, T., Potthoff, A., Michaelis, A., Schmiedel, C., Uhlmann, E., Blug, B. & Amann, T. (2015). Wear of abrasive media and its effect on abrasive flow machining results. *Wear,* 342–343, pp. 44–51. DOI:10.1016/j.wear.2015.08.013

Chaukura, N., Kefeni, K. K., Chikurunhe, I., Nyambiya, I., Gwenzi, W., Moyo, W., Nkambule, T. T. I., Mamba, B. B. & Abulude, F. O. (2021). Microplastics in the Aquatic Environment—The Occurrence, Sources, Ecological Impacts, Fate, and Remediation Challenges. *Pollutants*, 1(2), pp. 95–118. DOI:10.3390/POLLUTANTS1020009

Chen, C., Chen, L., Yao, Y., Artigas, F., Huang, Q. & Zhang, W. (2019). Organotin Release from Polyvinyl Chloride Microplastics and Concurrent Photodegradation in Water: Impacts from Salinity, Dissolved Organic Matter, and Light Exposure. *Environmental Science and Technology,* 53(18), pp. 10741–10752. DOI:10.1021/ACS.EST.9B03428/SUPPL_FILE/ES9B03428_SI_001.PDF

Choi, J., Kang, M. & Jung, J. H. (2015). Integrated micro-optofluidic platform for real-time detection of airborne microorganisms. *Scientific Reports*, 5, pp. 1–10. DOI:10.1038/srep15983

Corcoran, P. L. (2021). Degradation of Microplastics in the Environment. [in] Handbook of Microplastics in the Environment, pp. 1–12. *Springer International Publishing*. DOI:10.1007/978-3-030-10618-8_10-1

De Tender, C., Devriese, L. I., Haegeman, A., Maes, S., Vangeyte, J., Cattrijsse, A., Dawyndt, P. & Ruttink, T. (2017). Temporal Dynamics of Bacterial and Fungal Colonization on Plastic Debris in the North Sea. *Environmental Science and Technology*, 51(13), pp. 7350–7360. DOI:10.1021/ACS.EST.7B00697/SUPPL_FILE/ES7B00697_SI_001.PDF

Demeter, M. A., Lemire, J. A., Mercer, S. M. & Turner, R. J. (2017). Screening selectively harnessed environmental microbial communities for biodegradation of polycyclic aromatic hydrocarbons in moving bed biofilm reactors. *Bioresource Technology*, 228, pp. 116–124. DOI:10.1016/J.BIORTECH.2016.12.086

Dimassi, S. N., Hahladakis, J. N., Yahia, M. N. D., Ahmad, M. I., Sayadi, S. & Al-Ghouti, M. A. (2022). Degradation-fragmentation of marine plastic waste and their environmental implications: A critical review. *Arabian Journal of Chemistry*, 15(11), 104262. DOI:10.1016/J.ARABJC.2022.104262

Elsayed, A. A., Erfan, M., Sabry, Y. M., Dris, R., Gaspéri, J., Barbier, J. S., Marty, F., Bouanis, F., Luo, S., Nguyen, B. T. T., Liu, A. Q., Tassin, B. & Bourouina, T. (2021). A microfluidic chip enables fast analysis of water microplastics by optical spectroscopy. *Scientific Reports,* pp. 1–11. DOI:10.1038/s41598-021-89960-4

Farré, M. & Barceló, D. (2020). Microfluidic devices: biosensors. *Chemical Analysis of Food: Techniques and Applications, (Second Edition),* pp. 287–351. DOI:10.1016/B978-0-12-813266-1.00006-1

Flemming, H. C. & Wingender, J. (2010). The biofilm matrix. *Nature Reviews Microbiology*, 8(9), pp. 623–633. DOI:10.1038/nrmicro2415

Haiko, J. & Westerlund-Wikström, B. (2013). The role of the bacterial flagellum in adhesion and virulence. *Biology*, 2(4), pp. 1242–1267. DOI:10.3390/biology2041242

Headley, J. V., Gandrass, J., Kuballa, J., Peru, K. M. & Gong, Y. (1998). Rates of Sorption and Partitioning of Contaminants in River Biofilm. *Environmental Science & Technology*, 32(24), pp. 3968–3973. DOI:10.1021/ES980499L

Hook, A. L., Chang, C. Y., Yang, J., Luckett, J., Cockayne, A., Atkinson, S., Mei, Y., Bayston, R., Irvine, D. J., Langer, R., Anderson, D. G., Williams, P., Davies, M. C. & Alexander, M. R. (2012). Combinatorial discovery of polymers resistant to bacterial attachment. *Nature Biotechnology,* 30(9), pp. 868–875. DOI:10.1038/nbt.2316

Huston, A. L., Krieger-Brockett, B. B. & Deming, J. W. (2000). Remarkably low temperature optima for extracellular enzyme activity from Arctic bacteria and sea ice. *Environmental Microbiology,* 2(4), pp. 383–388. DOI:10.1046/j.1462-2920.2000.00118.x

Isobe, A., Uchida, K., Tokai, T. & Iwasaki, S. (2015). East Asian seas: A hot spot of pelagic microplastics. *Marine Pollution Bulletin*, 101(2), pp. 618–623. DOI:10.1016/J.MARPOLBUL.2015.10.042

Keswani, A., Oliver, D. M., Gutierrez, T. & Quilliam, R. S. (2016). Microbial hitchhikers on marine plastic debris: Human exposure risks at bathing waters and beach environments. *Marine Environmental Research*, 118, pp. 10–19. DOI:10.1016/J.MARENVRES.2016.04.006

Kiran, B. R., Kopperi, H. & Venkata Mohan, S. (2022). Micro/nano-plastics occurrence, identification, risk analysis and mitigation: challenges and perspectives. *Reviews in Environmental Science and Biotechnology*, 21(1), pp. 169–203. DOI:10.1007/S11157-021-09609-6/TABLES/3

Klein, S., Dimzon, I.K., Eubeler, J., Knepper, T.P. (2018). Analysis, Occurrence, and Degradation of Microplastics in the Aqueous Environment. [In:] Wagner, M., Lambert, S. (eds) Freshwater Microplastics . The Handbook of Environmental Chemistry, vol 58. Springer, Cham. DOI:10.1007/978-3-319-61615-5_3

Konry, T., Bale, S. S., Bhushan, A., Shen, K., Seker, E., Polyak, B. & Yarmush, M. (2012). Particles and microfluidics merged: Perspectives of highly sensitive diagnostic detection. *Microchimica Acta*, 176(3–4), pp. 251–269. DOI:10.1007/s00604-011-0705-1

Lange, J. P. (2021). Managing Plastic Waste-Sorting, Recycling, Disposal, and Product Redesign. *ACS Sustainable Chemistry and Engineering*, 9(47), pp. 15722–15738. DOI:10.1021/ACSSUSCHEMENG.1C05013/ASSET/IMAGES/LARGE/SC1C05013_0001.JPEG

Lee, H. J., Song, N. S., Kim, J. S. & Kim, S. K. (2021). Variation and Uncertainty of Microplastics in Commercial Table Salts: Critical Review and Validation. *Journal of Hazardous Materials*, 402, 123743. DOI:10.1016/J.JHAZMAT.2020.123743

Lorite, G. S., Rodrigues, C. M., de Souza, A. A., Kranz, C., Mizaikoff, B. & Cotta, M. A. (2011). The role of conditioning film formation and surface chemical changes on Xylella fastidiosa adhesion and biofilm evolution. *Journal of Colloid and Interface Science*, 359(1), pp. 289–295. DOI:10.1016/J.JCIS.2011.03.066

Lu, X. & Xuan, X. (2015). Inertia-enhanced pinched flow fractionation. *Analytical Chemistry,* 87(8), pp. 4560–4565. DOI:10.1021/ACS.ANALCHEM.5B00752/ASSET/IMAGES/ MEDIUM/AC-2015-007526_0008.GIF

Luo, S., Zhang, Y., Nguyen, K. T., Feng, S., Shi, Y., Liu, Y., Hutchinson, P., Chierchia, G., Talbot, H., Bourouina, T., Jiang, X. & Liu, A. Q. (2020). Machine Learning-Based Pipeline for High Accuracy Bioparticle Sizing. *Micromachines*, 11(12), 1084. DOI:10.3390/MI11121084

Mark, D., Haeberle, S., Roth, G., von Stetten, F. & Zengerle, R. (2010). Microfluidic lab-on-a-chip platforms: Requirements, characteristics and applications. *Chemical Society Reviews*, 39(3), pp. 1153–1182. DOI:10.1039/b820557b

Martin Alexander, (1971). Microbial Ecology. John Willey & Sons Inc.

Mauk, M. G., Chiou, R., Genis, V. & Carr, E. (2013). *Image analysis of microfluidics: Visualization of flow at the microscale*. ASEE Annual Conference and Exposition, Conference Proceedings. DOI:10.18260/1-2--19693

Mekaru, H. (2020). Effect of Agitation Method on the Nanosized Degradation of Polystyrene Microplastics Dispersed in Water. *ACS Omega*, 5(7), pp. 3218–3227. DOI:10.1021/ACSOMEGA.9B03278/ASSET/IMAGES/LARGE/AO9B03278_0006.JPEG

Oberbeckmann, S., Löder, M. G. J. & Labrenz, M. (2015). Marine microplastic-associated biofilms – a review. *Environmental Chemistry*, 12(5), pp. 551–562. DOI:10.1071/EN15069

Osman, A. I., Hosny, M., Eltaweil, A. S., Omar, S., Elgarahy, A. M., Farghali, M., Yap, P. S., Wu, Y. S., Nagandran, S., Batumalaie, K., Gopinath, S. C. B., John, O. D., Sekar, M., Saikia, T., Karunanithi, P., Hatta, M. H. M. & Akinyede, K. A. (2023). Microplastic sources, formation, toxicity and remediation: a review. *Environmental Chemistry Letters*, 21(4), pp. 2129–2169. DOI:10.1007/S10311-023-01593-3

Pattanayak, P., Singh, S. K., Gulati, M., Vishwas, S., Kapoor, B., Chellappan, D. K., Anand, K., Gupta, G., Jha, N. K., Gupta, P. K., Prasher, P., Dua, K., Dureja, H., Kumar, D. & Kumar, V. (2021). Microfluidic chips: recent advances, critical strategies in design, applications and future perspectives. *Microfluidics and Nanofluidics*, 25(12), pp. 1–28. DOI:10.1007/S10404-021-02502-2/FIGURES/17

Pauli, N. C., Petermann, J. S., Lott, C. & Weber, M. (2017). Macrofouling communities and the degradation of plastic bags in the sea: An in situ experiment. *Royal Society Open Science*, 4(10). DOI:10.1098/rsos.170549

Qiu, X., Qi, Z., Ouyang, Z., Liu, P. & Guo, X. (2022). Interactions between microplastics and microorganisms in the environment: Modes of action and influencing factors. *Gondwana Research,* 108, pp. 102–119. DOI:10.1016/J.GR.2021.07.029

Regnault, C., Dheeman, D. S. & Hochstetter, A. (2018). Microfluidic Devices for Drug Assays. *High-Throughput,* 7(2), p 18. DOI:10.3390/HT7020018

Ren, K., Zhou, J. & Wu, H. (2013). Materials for microfluidic chip fabrication. *Accounts of Chemical Research,* 46(11), pp. 2396–2406. DOI:10.1021/ar300314s

Renner, L. D. & Weibel, D. B. (2011). Physicochemical regulation of biofilm formation. *MRS Bulletin*, 36(5), pp. 347–355. DOI:10.1557/MRS.2011.65

Romera-Castillo, C., Pinto, M., Langer, T. M., Álvarez-Salgado, X. A. & Herndl, G. J. (2018). Dissolved organic carbon leaching from plastics stimulates microbial activity in the ocean. *Nature Communications,* 9(1), pp. 1–7. DOI:10.1038/s41467-018-03798-5

Rosenberg, M., Bayer, E. A., Delarea, J. & Rosenberg, E. (1982). Role of Thin Fimbriae in Adherence and Growth of Acinetobacter calcoaceticus RAG-1 on Hexadecane. *Applied and Environmental Microbiology*, 44(4), pp. 929–937. DOI:10.1128/AEM.44.4.929-937.1982

Rummel, C. D., Jahnke, A., Gorokhova, E., Kühnel, D. & Schmitt-Jansen, M. (2017). Impacts of biofilm formation on the fate and potential effects of microplastic in the aquatic environment. *Environmental Science and Technology Letters*, 4(7), pp. 258–267. DOI:10.1021/ACS.ESTLETT.7B00164/ASSET/IMAGES/LARGE/EZ-2017-00164X_0001.JPEG

Russell, N. J. (1990). Cold adaptation of microorganisms. *Philosophical Transactions - Royal Society of London*, B, 326(1237), pp. 595–611. DOI:10.1098/rstb.1990.0034

Sauer, K. (2003). The genomics and proteomics of biofilm formation. *Genome Biology*, 4(6), pp. 1–5. DOI:10.1186/GB-2003-4-6-219/FIGURES/1

Sgier, L., Freimann, R., Zupanic, A. & Kroll, A. (2016). Flow cytometry combined with viSNE for the analysis of microbial biofilms and detection of microplastics. *Nature Communications*, 7(1), pp. 1–10. DOI:10.1038/ncomms11587

Shrirao, A. B., Fritz, Z., Novik, E. M., Yarmush, G. M., Schloss, R. S., Zahn, J. D. & Yarmush, M. L. (2018). Microfluidic flow cytometry: The role of microfabrication methodologies, performance and functional specification. *Technology*, 06(01), pp. 1–23. DOI:10.1142/s2339547818300019

Teuten, E. L., Rowland, S. J., Galloway, T. S. & Galloway, T. S. (2007). Potential for Plastics to Transport Hydrophobic Contaminants. *ACS Publications*, 41(22).

Tokiwa, Y. & Calabia, B. P. (2004). Degradation of microbial polyesters. *Biotechnology Letters*, 26(15), pp. 1181–1189. DOI:10.1023/B:BILE.0000036599.15302.E5/METRICS

Tu, C., Zhou, Q., Zhang, C., Liu, Y. & Luo, Y. (2020). Biofilms of Microplastics. *Handbook of Environmental Chemistry*, 95, pp. 299–317. DOI:10.1007/698_2020_461

Vaid, M., Sarma, K. & Gupta, A. (2021). Microplastic pollution in aquatic environments with special emphasis on riverine systems: Current understanding and way forward. *Journal of Environmental Management*, 293, 112860. DOI:10.1016/J.JENVMAN.2021.112860

Verma, R., Vinoda, K. S., Papireddy, M. & Gowda, A. N. S. (2016). Toxic Pollutants from Plastic Waste- A Review. *Procedia Environmental Sciences*, 35, pp. 701–708. DOI:10.1016/J.PROENV.2016.07.069

Wang, M. H., He, Y. & Sen, B. (2019). Research and management of plastic pollution in coastal environments of China. *Environmental Pollution*, 248, pp. 898–905. DOI:10.1016/J.ENVPOL.2019.02.098

Wang, T., Wang, L., Chen, Q., Kalogerakis, N., Ji, R. & Ma, Y. (2020). Interactions between microplastics and organic pollutants: Effects on toxicity, bioaccumulation, degradation, and transport. *Science of the Total Environment*, 748, 142427. DOI:10.1016/j.scitotenv.2020.142427

Wellner, N. (2013). Fourier transform infrared (FTIR) and Raman microscopy: principles and applications to food microstructures. *Food Microstructures: Microscopy, Measurement and Modelling*, pp. 163–191. DOI:10.1533/9780857098894.1.163

Wimpenny, J. W. T. (1996). Laboratory growth systems in biofilm research. *Cells and Materials*, 6(1–3), pp. 221–232.

Wright, S. L. & Kelly, F. J. (2017). Plastic and Human Health: A Micro Issue? *Environmental Science and Technology,* 51(12), pp. 6634–6647. DOI:10.1021/acs.est.7b00423

Writer, J. H., Ryan, J. N. & Barber, L. B. (2011). Role of biofilms in sorptive removal of steroidal hormones and 4-nonylphenol compounds from streams. *Environmental Science and Technology*, 45(17), pp. 7275–7283. DOI:10.1021/es2008038

Wu, Y., Xia, L., Yu, Z., Shabbir, S. & Kerr, P. G. (2014). In situ bioremediation of surface waters by periphytons. *Bioresource Technology*, 151, pp. 367–372. DOI:10.1016/j.biortech.2013.10.088

Yong, C. Q. Y., Valiyaveettil, S. & Tang, B. L. (2020). Toxicity of Microplastics and Nanoplastics in Mammalian Systems. *International Journal of Environmental Research and Public Health,* 17(5), 1509. DOI:10.3390/IJERPH17051509

Yu, Y., Li, H., Zeng, Y. & Chen, B. (2009). Extracellular enzymes of cold-adapted bacteria from Arctic sea ice, *Canada Basin. Polar Biology*, 32(10), pp. 1539–1547. DOI:10.1007/s00300-009-0654-x

Zhang, K., Hamidian, A. H., Tubić, A., Zhang, Y., Fang, J. K. H., Wu, C. & Lam, P. K. S. (2021). Understanding plastic degradation and microplastic formation in the environment: A review. *Environmental Pollution*, 274, 116554. DOI:10.1016/J.ENVPOL.2021.116554

Zhang, Y., Kang, S., Allen, S., Allen, D., Gao, T. & Sillanpää, M. (2020). Atmospheric microplastics: A review on current status and perspectives. *Earth-Science Reviews,* 203, 103118. DOI:10.1016/j.earscirev.2020.103118

Zhang, Y., Zhang, M. & Fan, Y. (2022). Assessment of microplastics using microfluidic approach. *Environmental Geochemistry and Health*, 45(3), pp. 1045–1052. DOI:10.1007/S10653-022-01262-4/METRICS

Zhu, K., Jia, H., Zhao, S., Xia, T., Guo, X., Wang, T. & Zhu, L. (2019). Formation of Environmentally Persistent Free Radicals on Microplastics under Light Irradiation. *Environmental Science and Technology*, 53(14), pp. 8177–8186. DOI:10.1021/ACS.EST.9B01474/SUPPL_FILE/ES9B01474_SI_001.PDF