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Microplastics in the Marine Environment and Deep-Sea Sediment Contamination: A Review

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Submitted in Partial Completion of the
Requirements for Commonwealth Honors in Geological Sciences

Bridgewater State University

May 9, 2022

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Abstract

This review discusses what microplastics are and how they are continuously impacting the marine environment, and ultimately, human life. Plastic has been the number one used material for decades for industrial and recreational purposes. Its cost effectiveness, durability, and lightness are what manufacturers and consumers desire most, making plastic the most abundant pollutant in the world. Understanding how plastic pollution is broken down into microplastics and how these fragmented pieces of waste are classified can help researchers identify ways to prevent the additional input of microplastics in the marine environment. These microscopic particles of debris have been sampled from deep-sea sediment, meaning plastic pollution has been transported to great distances across various oceans. By using the knowledge of natural processes regarding the Earth's rotation and the formation of transport currents throughout the water column, discussing how plastic pollution and microplastics reach these depths can be supported. Although the presence of microplastic in the ocean has become a major issue in terms of accumulation, marine life is being threatened due to the toxic elements within many plastic polymers. By conducting further research on microplastics and understanding how they impact the marine environment, manufacturers and consumers become educated on the dangers of plastic use, leading to goals of reducing the amount of plastic waste continuously accumulating all over the world.

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1 Introduction

The first synthetic plastic polymer was invented just over a century ago in 1907, opening the world to an age of production growth and economic benefit. The cheap, light weight material quickly began to be used by manufacturers for packaging with an annual production of 245 million tons of plastic by the year 1950 (Andrady, 2011). Industries favored plastic packaging for its strength, flexibility, and ability to increase shelf life of various products. The creation of plastic was positive overall, however, the boom in plastic usage has resulted in the accumulation of plastic waste due to its immense durability and was first discovered to be accumulating in the ocean in the early 1970s (Andrady, 2011). Manufacturers often incorporate chemical additives to the plastic polymer to increase polymer strength and life span, taking hundreds of years for plastic to breakdown. When thinking of sources to sinks throughout the environment, any plastic that is not properly disposed of is likely to enter waterways and pollute ecosystems. Ultimately, these waterways lead to the ocean, where plastic pollution has accumulated for decades. The increasing consumer use of plastics has created more plastic pollution to enter the marine environment, especially along coastlines due to recreation and beach usage. By 1988, the United States alone has produced 30 million tons of plastic waste annually (Derraik, 2002), and nearly half of the worlds overall plastic waste is being produced by Asia (Andrady, 2017). All over the world, plastic usage has become a major concern to marine health and is only growing into a greater issue.

To understand why plastic waste accumulates in the ocean, it is important to recognize the chemical properties of polymers. Polymers are composed of long chain-like molecules made up of repeating (poly) chemical structure units (mers) (Andrady, 2017). Van der Waals force

describes the strength between these units by identifying the repulsion and attraction forces between the molecular chains. The longer the molecular chain, the stronger the polymer will be, making plastic an incredibly durable material. Plastic polymers are also hydrophobic, making them excellent at repelling water (Constant et al., 2021), as they are readily used to protect other products during transportation against accidents. Plastics are hydrophobic, meaning they repel water and are attracted to like materials. Plastic particles attract to each other, resulting in the accumulation of microplastics in areas across the vast ocean.

Over the past few decades, environmental scientists and researchers have identified microplastics as a growing threat to the marine environment. Microplastics are fragmented particles of plastic pollution that do great harm to their surrounding environment, especially in the ocean. They are formed by the physical and chemical breakdown of plastic waste and are easily transported across the ocean since plastic is an extremely buoyant material with varying densities that are less than the density of saltwater (Andrady, 2011). There are some instances where microplastics enter the marine environment directly, without being fragmented as they are manufactured to be microscopic in size. Marine life and even humans are being directly impacted by the presence of microplastics, creating a push for environmental legislation towards plastic usage all over the world. By learning how microplastics are created and where they originate from, consumers can work to prevent any plastic waste and microplastics from entering the marine environment.

2 Overview of Microplastics

The presence of plastic pollution in the ocean has become a prevalent environmental concern worldwide. Although larger pieces of plastic debris pose a threat to the marine environment, what these pieces of trash can become may be even more dangerous to the Earth. Microplastics are derived from plastic waste by humans, which is broken down and carried throughout waterways such as rivers and lakes. Storm drains collect plastic pollution left behind in parking lots, roads, and sidewalks when large amounts of rainfall occur, and runoff picks up any debris in its way. Pollution like this is inevitably dumped into waterways that lead to the ocean. Microplastics can be identified and analyzed to help determine how and from where they originate. To do this, it is important to understand what the different types of microplastics found in the marine environment are.

2.1 Classification of Microplastics and Plastic Pollution

Plastics pollution that has been broken down into smaller pieces are classified by size, namely. Because these smaller pieces are typically microscopic in size, the term “microplastics” is used widely. However, there are three classifications for these tiny plastic particles. The term “macroplastic” refers to any plastic particle that is greater than or equal to 10mm (millimeter) in diameter (Halle et al., 2016). A macroplastic, for example, is a plastic water bottle or bag, or a piece of plastic packaging that may have been broken apart from its original state yet is 10mm or more in diameter. When looking at plastic particles that are smaller than a microplastic, the term “mesoplastic” is used. These are plastic particles that range from 5mm to 10mm in diameter. Finally, the term “microplastic” refers to a particle of plastic that has a diameter from 1µm

(micrometer) to 5mm (Halle et al., 2016). This review will focus on plastic particles in the marine environment that are classified as microplastics.

To further classify microplastics, it is important to know if the microplastic was derived from the breakdown of larger meso- or macroplastics, or if it was manufactured as a microplastic to begin with. For plastics that are manufactured to be of microscopic size, such as those typically used in facial cleansers and personal products, the term “primary microplastic” is used (Cole et al., 2011). These man-made plastic particles are given the name microbeads and marketed towards consumers as exfoliants. Primary microplastics are easily transported through sewers and waterways due to their small size to begin with. The term “secondary microplastics” is used to describe a plastic particle that originated as a macro- or mesoplastic and has become a microplastic due to fragmentation and the breakdown of these larger pieces of plastic debris by physical or chemical weathering processes (Cole et al., 2011). The plastic pollution from which a secondary microplastic originates from could have previously resided either on land or in the ocean before fragmentation (Cole et al., 2011), although identifying the origin of secondary microplastics correctly is not yet reliable.

2.2 Sources of Primary and Secondary Microplastics

Both primary and secondary microplastics can enter the marine environment by either direct or indirect disposal (Cole et al., 2011). Direct disposal is the purposeful dumping of plastic pollution into waterways and the ocean, typically the result of industrial activity. Indirect disposal of plastic waste mainly occurs from litter and trash that should have been sent to a landfill but was instead released to the environment due to wind and poor disposal techniques. Plastic pollution that was not properly disposed of can be found in parking lots and major

roadways, resulting in them being collected in storm drains and sewer systems. The sources of microplastics can be identified among four main categories: beaches and recreation, manufacturers and production waste, fishing and boating industry waste, and waste from the use of cosmetics and personal care products.

2.2.1 Beaches and Recreation

Nearly half of the world's population resides within 50 miles of coastlines and waterways as lakes, rivers, and beaches are used for recreation (Moore, 2008). Roughly 80% of secondary microplastics in the ocean is sourced back to beach litter and other land-based origins that were the result of indirect disposal (Andrady, 2011). Plastic litter that is left on beach sand or along lakes and rivers are exposed to intense heat and sunlight, which can increase the breakdown rate of plastic polymers. These broken-down pieces of plastic debris are likely to enter the ocean by being picked up and carried away by ocean currents, producing microplastics to exist in the ocean. Coastal marine life is greatly endangered by the presence of plastic debris left behind by beachgoers, as plastic can be life threatening for many species. The amount of plastic pollution in the ocean caused by litter left behind at beaches and other sites of recreation should be concerning, yet these are not the only major source.

2.2.2 Manufacturers and Production

Manufacturing industries favor the use of plastic materials for packaging and production for its durability, flexibility, and low cost. Hundreds of thousands of products that are sent out to consumers are often transported within further plastic packaging to ensure the products are protected during travel. Waste produced by production processes are less likely to be recycled for further use, leading to their disposal in the environment. This plastic waste is likely to be

fragmented and carried toward waterways where it will eventually become plastic pollution in the ocean. It is estimated that merchant ships across the world dump over 600,000 plastic containers from production material into the ocean each day (Derraik, 2002).

The use of resin plastic pellets has become a major contributor to microplastic pollution in the marine environment. Resin pellets are granules of plastic used by manufacturers to create a uniform composition of their plastic products during the molding process (Cole et al., 2011). Plastic water bottles are one of the main products made using resin pellets. These pellets help plastic water bottles hold their shape and remain durable for consumer use. Although resin pellets are used primarily during production, there has been occurrences where ships carrying granules for manufacturers may cause accidental spillage of the material during transport (Cole et al., 2011), meaning these small pieces of plastic are being directly dumped into the marine environment.

2.2.3 Fishing and Boating Industry

The fishing and boating industry creates ship-sourced pollution by direct or indirect disposal. In 1975, it was estimated that the world's fishing fleet dumped nearly 135,400 tons of plastic gear such as rope and nets directly into the ocean once they became no longer useful (Derraik et al., 2002). Fishing gear is often buoyant due to it being primarily composed of synthetic polymers. Because of this, nets and rope can drift to variable depths where weathering and degradation processes occur to breakdown the plastic equipment, adding to the concentration of microplastics in the ocean.

A recent investigation by Song et al. (2014) off the coast of South Korea identified another pollutant associated with activity by the boating and fishing industries. Particles of paint

that have been chipped and removed from the exterior of ships have been found within the surface layer of coastal South Korean seas. These particles were analyzed and confirmed to be alkyd-based chips of paint coatings. Alkyd paints are applied to boat exteriors, whether on the sides and underside or along the deck surface, to protect the wood or metal material of the boat from corrosion. The friction due to waves crashing along the sides of a boat can cause the external paint of a boat to be stripped away. In addition, activity by the fishing industry such as pulling nets onto the deck or cleaning and scrubbing the deck surface can also introduce paint chips into the ocean. The presence of paint particles within the surface of the ocean adds to the growing concern of microplastic pollution and may also be toxic to the marine environment due to chemicals from the paint being leached into the surrounding water.

2.2.4 Cosmetics

It may be a surprise to some that many cosmetic products and personal care products contain plastic particles. Plastic material made up of synthetic, water insoluble polymers are added to a variety of products to achieve desired properties and functionality (Leslie, 2014). Properties such as viscosity regulation, skin conditioning, exfoliation, and thermal regulation are achieved in products like moisturizer, skin cleansers, shampoo, sunscreen, makeup and more. Products with abrasive characteristics are typically marketed for exfoliation by containing ‘microbeads’ or ‘pore-cleansing’ particles (Fendall, 2009). Due to many being ‘rinse off’ products such as skin cleansers and shampoo, any microplastic particles within the products are drained into household water systems and eventually into local waterways (Leslie, 2014). Although a portion of microplastics from cosmetics and products are retained in what is known

as sewage sludge, there is a significant amount that is emitted further leading to the marine environment.

3 Breakdown of Plastic Pollution

3.1 Physical Weathering of Plastic Pollution

The production of microplastics starts with the physical breakdown and weathering of plastic pollution in the marine environment. Secondary microplastics are the result of macroplastic debris being fragmented into smaller and smaller particles until they are eventually measured in micrometers (μm) in diameter (Cole et al., 2011). The physical breakdown of plastic debris into secondary microplastics can occur either on land or in the open ocean, which affects the intensity of weathering done on a plastic material differently. On land, there is greater surface area of the plastic material that is exposed to direct sunlight compared to plastic in the ocean which may only be exposed on one side depending on its shape. Fragmentation of plastic on land occurs more frequently than plastics in the ocean due to the friction of rocks and minerals in contact with the plastics, as well as enhanced oxidation rates from the direct exposure to oxygen in the atmosphere compared to the amount of oxygen in the ocean (Halle et al., 2016). In the ocean, plastic debris is still exposed to mechanical and physical elements resulting in fragmentation, however not as intensely compared to breakdown on land. Wave action and collision with coral or underwater rock formations are two main weathering mechanisms responsible for the physical breakdown of plastic pollution, creating secondary microplastics.

Primary microplastics are particles of plastic pollution that are manufactured to be microscopic in size. Although this debris is already of microscopic size, further physical weathering can occur. Particles of plastic pollution that have already been broken down are more susceptible to additional physical weathering. Shear and tensile stress on a previously weathered plastic particle is greater, resulting in fracturing and cracking of the particle's surface (Halle et

al., 2016). This weakening of the plastic's surface can lead to more fracturing of the particle, as well as more rapid chemical degradation of the particle (Halle et al., 2016). As a consequence, physical weathering is an ongoing process affecting primary and secondary microplastics and other forms of plastic pollution, on land, and especially in the marine environment.

3.2 Chemical Degradation of Polymers

Although physical weathering conditions do influence the breakdown rate of plastic debris in the ocean, there is another process which also affects the fragmentation of plastic pollution. Degradation is a term used to describe the chemical processes that lead to a decline of molecular properties in polymers (Gewert et al., 2015). When microplastics are exposed to high water temperatures, sunlight (both visible and UV radiation), or biological foulants, they are prone to further breakdown by degradation. In this study, the most typical types of degradation pathways were reviewed, namely biodegradation, photodegradation, photo-oxidative degradation, auto-oxidative degradation, thermo-oxidative degradation, and hydrolytic degradation (Andrady, 2011). These pathways occur depending on what conditions microplastics are exposed to in the marine environment, although they can occur in terrestrial environments as well. Particles of plastic waste on beaches are more likely to degrade faster than those in an aquatic setting since they are directly exposed to sunlight and extreme temperatures. In terms of this review, microplastics in the marine environment are degraded by the same processes that affect particles on land, however the rate of degradation is much slower.

3.2.1 Degradation Pathways

When looking at the six common types of plastic identified from plastic debris and microplastic sampling in the ocean, each undergoes differing degradation pathways due to their

varying molecular structure. These six polymers are known as polyethylene (PE), polypropylene (PP), polystyrene (PS), polyvinyl chloride (PVC), polyethylene terephthalate (PET), and polyurethane (PU). To further understand how the different polymer materials degrade, it is important to note what happens to polymers during each degradation pathway that is likely to occur due to the presence of plastic in the marine environment. Biodegradation occurs when microbial organisms interact with the molecular structure of polymers. These microbial specimens convert the organic substrates of polymers into carbon dioxide (CO₂) and water (H₂O) (Gewert et al., 2015). Photodegradation is the result of sunlight directly affecting polymer structure in the plastic debris, often resulting in discoloration and brittleness. Photo-oxidative degradation is the occurrence of sunlight and oxygen reacting to cause the polymer surface to break down. Auto-oxidative degradation and thermo-oxidative degradation take place in the presence of oxygen, but the temperature of the surroundings will impact the degradation pathway of the polymer. At average temperatures, roughly 20°C at the ocean surface, auto-oxidation occurs meaning oxygen is introduced to the molecular structure of a polymer, resulting in a constant rate of oxidation. When temperatures are higher due to induced stress or weather conditions, this form of degradation is known as thermo-oxidation (Gewert et al., 2015). Hydrolytic degradation, or hydrolysis, is one of the more commonly occurring breakdown pathways for microplastic degradation in the marine environment, since they are directly impacted by the surrounding seawater. The more acidic ocean water is, the higher the rate of hydrolysis degradation (Gewert et al., 2015). In terms of molecular structure, hydrolysis breaks up the chains of polymer molecules into smaller chains, leading to a decrease in molecular weight due to the exposure to water. To broaden the classification of these pathways, two categories have been identified: abiotic and biotic degradation. Abiotic degradation includes

processes which do not include the presence of biological interactions with the polymer (photo-, photo-oxidative, auto-oxidative, thermo-oxidative, and hydrolytic degradation), while biotic degradation does include biological matter to breakdown plastic polymers (biodegradation). Each of these collective forms of degradation play a major role in the chemical breakdown of the polymer structure at the molecular level. The breakdown then depends on the conditions to which plastic debris is exposed as well as to the type of plastic polymer itself.

The first of the six most common plastics analyzed by Gewert et al. (2015), is polyethylene (PE). In the marine environment, microplastic PE particles undergo auto-oxidative degradation, which causes oxygen to be incorporated into the chemical structure of PE polymers. This increase in oxygen amounts leads to the breakdown of the polymer and the release of toxins produced by the degradation process. When microplastic polymers are further broken down by degradation, additives that are commonly added to the original plastic material are easily leached into the seawater. This can be explained by additives not being covalently bonded to a polymer, meaning it is more likely these additives can be stripped from the polymer and expelled into the surrounding ocean environment. When focusing on PE polymer additives, those that are leached into oceanwater as a product of auto-oxidation are identified as propane, propene, ethane, ethene, butene, and hexene. Once this abiotic pathway occurs, PE polymers can be further broken down by biodegradation, producing CO₂ and H₂O.

Polypropylene (PP) is another type of plastic that has been commonly identified by analyzing plastic pollution in the ocean. PP has a lower stability compared to PE because it has more carbon atoms in its molecular structure. This means PP polymer is prone to abiotic degradation because of these carbon atoms that can be stripped with less effort than those in PE.

PP undergoes a similar reaction to PE where the incorporation of oxygen in its chemical structure produces multiple toxins which are leached into the oceanwater, reducing the molecular weight of the polymer.

The polymer polystyrene (PS), although a durable plastic, is one of the more brittle plastics that is susceptible to weathering by physical and chemical processes. PS polymers typically undergo thermo-oxidation due to extensive UV radiation and high temperatures in surrounding waters. When UV radiation causes thermo-oxidation to occur in PS polymers, energy transfers to the nearest carbon-hydrogen (C-H) bond throughout the polymer's molecular structure. The transfer of energy to these C-H bonds results in the breakdown of the polymer, as well as cleavage of the hydrogen atoms in PS molecules (Gewert et al., 2015). With cleavage fractions in PS molecules, it is easier for them to be fragmented and further degraded due to their brittle characteristics and weak fracture points. Unlike PE and PP, PS does not break down via biodegradation (Gewert et al., 2015).

When comparing all six types of plastic commonly found in the marine environment, the least stable of the polymers is PVC, polyvinyl chloride. PVC is the most sensitive of the six polymers to UV radiation, making it prone to photodegradation (Gewert et al., 2015). During photodegradation of PVC, carbon-chlorine (C-Cl) bonds are broken apart by the exposure to UV light, releasing chlorine ions. This is also known as dichlorination. Dichlorination is enhanced and occurs at faster rates in marine conditions. Humidity, mechanical stress, high temperatures, and the presence of other chemicals can accelerate dichlorination rates as well. Chlorine increases a polymer's resistance to aquatic biodegradation, resulting in the occurrence of abiotic degradation as stated previously as the process of dichlorination (Gewert et al., 2015). PVC

polymer is molecularly capable of carrying a wide range of additives, which can eventually be leached into the surrounding seawater just as those in PE and PP polymers. Lastly, discoloration of the polymer can occur, which is not observed with the other polymers analyzed.

Polyethylene terephthalate (PET) is susceptible to three abiotic degradation pathways, resulting in toxin production and visual effects. PET is prone to photodegradation, which leads to cleavage of bonds and the formation of carboxylic acid due to the breakdown of the polymers molecular chain structure. Of the polymers studied by Gewert et al. (2015), PET is the most susceptible to undergo hydrolysis, which at room temperature is a slow process. However, the low temperatures in the marine environment make hydrolysis the most important degradation process of PET polymers. When ocean waters are more acidic, hydrolysis rates increase which results in the formation of carboxylic acid much like what is observed for the PVC end groups. PET polymers are also likely to degrade by photo-induced oxidation and can result in the visual effect of yellowing of the polymer.

Concluding the list of the six most common types of plastic polymers identified from the marine environment, polyurethane (PU) is composed of large complex polymers with carbon, oxygen, and nitrogen (Gewert et al., 2015). These ions within the PU molecular chain structure are more readily degraded overtime. Photo-oxidation, hydrolysis, and biodegradation are the major pathways of degradation for PU polymers, which ultimately leads to the production of hydroperoxides released into the surrounding ocean water. Fungal biodegradation is prevalent for PU polymers, as microorganisms gradually cause the degradation and breakdown of polyester segments of PU easily (Gewert et al., 2015).

3.3 Properties of Polymers After Degradation

When a microplastic particle undergoes physical or chemical degradation, the particle has been altered with new physical properties. Degraded microplastics can be identified by comparing their observed physical characteristics with those of the same original polymer type. There are four main indicators of degradation of a microplastic particle: color, surface morphology, crystalline structure, and density. The physical effects of solar degradation, thermal and oxidative degradation, and biodegradation, as well as the new physical properties of the microplastic polymers are shown in Figure 1. Guo and Wang (2019) represent both primary microplastics and secondary microplastics (macroplastics that have been broken down) and the types of breakdowns they encounter throughout the marine environment.

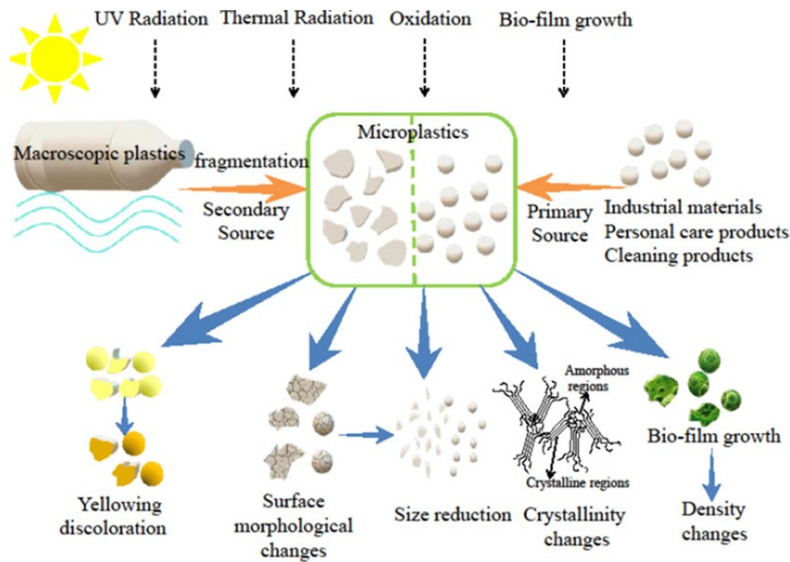


Figure 1. Changes in properties of microplastics after degradation (Guo and Wang, 2019).

The color of a microplastic is one of the first characteristics that is observed from chemical degradation. When a microplastic is exposed to intense sunlight and solar radiation, it

is prone to photodegradation. Microplastics that are originally white in color and eventually photodegraded become tinted yellow due to UV radiation. The yellowing rate of white polymers differs in plastic debris being degraded on land than in the ocean. Because of exposure to oxygen and the protection of biofilm build up by fouling, yellowing of photodegraded polymers is a slower process in the marine environment than on land (Guo and Wang, 2019).

Mechanical forces in the ocean that cause the fragmentation of plastic debris leads to morphological changes on the surface of microplastics. The friction produced from colliding particles or hydraulic forces on a plastic particle covers the surface of the polymer with cracks and fractures (Guo and Wang, 2019). This creates a weakened polymer surface, allowing for further physical and chemical breakdown of the particle since there is more surface area due to an abundance of fractures on the plastic. The impact on a microplastic particle by abrasion of mechanical weathering can lead to the alteration of not only the physical surface morphology of the particle, but the crystalline component as well (Guo and Wang, 2019). When the surface of a microplastic particle is fractured, that fracture is likely to become bigger and form deeper into the interior of the particle, which changes the crystalline structure of the polymer, often reducing it. As further weathering and degradation occur, the fractures along the surface of the microplastic particle are worsened, leading to the decrease of crystallinity of the polymer.

The density of a microplastic is measured by the density of the polymer it is composed of, as well as the density of the biofilm that may be covering it due to biofouling. Densities of the six principal plastic polymers are shown in Table 1. The colonization of microorganisms such as algae or bacteria on microplastics in the ocean increases the particles' density (Guo and Wang, 2019). Degradation by biofouling plays a major role in the distribution of microplastics

throughout the water column, from the surface of the water to the sediment of the seafloor. The final density (g/L) of a microplastic particle in the marine environment when in contact with biofilm is shown by Equation 1., where ρ is the density of the bio-fouled microplastic, ρ_0 is the initial density of the polymer, ρ_f is the density of the biofilm, d is the thickness of the biofilm in meters, and R_0 is the radius of the microplastic. The initial density of the polymer must be less than the density of the microplastic after biofouling.

Densities of principal types of plastic polymers	
Polymer Name	Density (g/cm³)
Polyethylene	0.917 – 0.965
Polypropylene	0.9 – 0.91
Polystyrene	1.04 – 1.1
Polyvinyl chloride	1.16 – 1.58
Polyethylene terephthalate	1.37 – 1.45
Polyurethane	1.2

Table 1. Density of six common plastic polymers in (Bellasi et al., 2021).

$$\rho = \rho_0 + \rho_f \frac{3d}{R_0}$$

Equation 1. Density of biofouled plastic polymer (Guo and Wang, 2019).

4 Transport of Microplastics

The detection of plastic pollution has been recorded all over the world, mainly along the surface of the ocean. Plastic is composed of polymers that are overall buoyant materials, explaining why there is an accumulation of floating plastic waste. When plastic pollution is fragmented and degraded into microplastics, these small particles can be easily transported throughout the marine environment. Floating plastics at the ocean surface have been found throughout the water column, meaning they are able to travel from the ocean surface, to varying depths of the open ocean, and may eventually reside along the seafloor. When microplastics travel throughout the water column, they are suspended in water because the polymer composition of the particle makes it neutrally buoyant. This gives way to understanding how the density of polymers must undergo some type of degradation in order for the transportation of microplastics throughout the water column to occur. The current understanding of how microplastics are transported throughout the marine environment is limited, however a variety of theories for this transport have been proposed. When discussing movement of microplastics in the marine environment, particles may be transported horizontally and vertically. Horizontal transport is defined as the movement of the particle across the ocean surface. Vertical transport is defined as how the movement of the particle from the surface of the ocean down to the ocean floor.

4.1 Horizontal Transport

One theory to explain the horizontal transport of microplastics involves geostrophic currents. This is the balance between a pressure-gradient force, in this case gravity, and the Coriolis effect due to the Earth's rotation. As the Earth rotates, the Coriolis effect causes any

object on the Earth's surface to deflect from its original path of motion. The direction of the deflection depends on whether the object is located within the Northern Hemisphere or the Southern Hemisphere: objects are deflected to the right in the Northern Hemisphere and to the left in the Southern Hemisphere. When the Coriolis forces and gravitational forces are equal, geostrophic balance occurs. This is modeled in Figure 2, indicating the direction of the Coriolis effect and gravitational forces on an object, along with the geostrophic flow direction. The path a microplastic particle could take would not be in the direction of gravity from a high to low water elevation, but in a direction perpendicular to the sum of the forces exerted by the Coriolis effect and gravity. These geostrophic currents create the specific direction of flow along the surface of ocean water which microplastics follow across great distances (Onink et al., 2019).

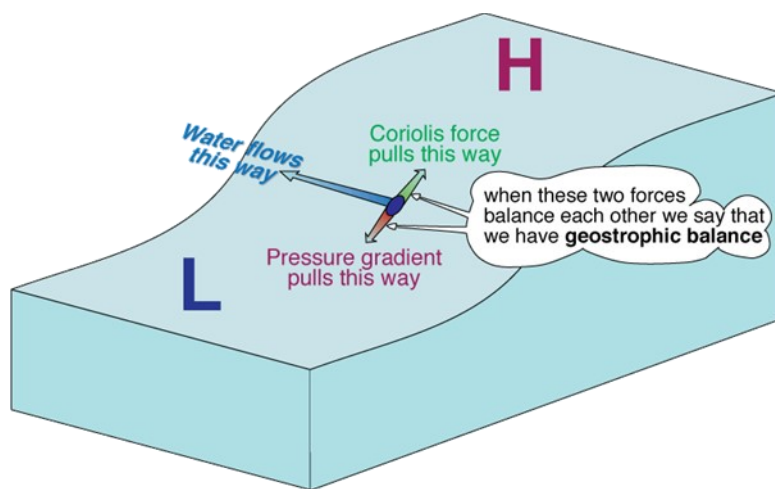


Figure 2. The direction of geostrophic flow by the balance of the Coriolis effect and the pressure-gradient force (Geostrophic Currents, SEOS).

With the knowledge of geostrophic flow processes, understanding the horizontal transport pathway of a microplastic in the marine environment provides an explanation for how macro- and microplastics accumulate on the surface of the ocean. Ocean gyres are large circular currents formed by wind patterns and geostrophic currents due to both the Coriolis effect and the

Earth's rotation. Because gyres are circular, plastic pollution floating in the ocean is likely to become trapped within the current and accumulate over time (Onink et al., 2019). Five ocean gyres have been identified and are named relative to their location: the North Atlantic Gyre, the South Atlantic Gyre, the North Pacific Gyre, the South Pacific Gyre, and the Indian Ocean Gyre (Onink et al., 2019). These major circulation zones shown in Figure 3 are the perfect environment for plastic debris in the ocean to accumulate, giving them the notorious name of a "garbage patch". As more plastic pollution enters the marine environment, each garbage patch within the five gyres grows larger in size overtime. Currently, the largest accumulation of plastic among the five gyres is known as the Great Pacific Garbage Patch (LeBreton et al., 2018) and is quickly growing with the continuous use and disposal of plastic worldwide.

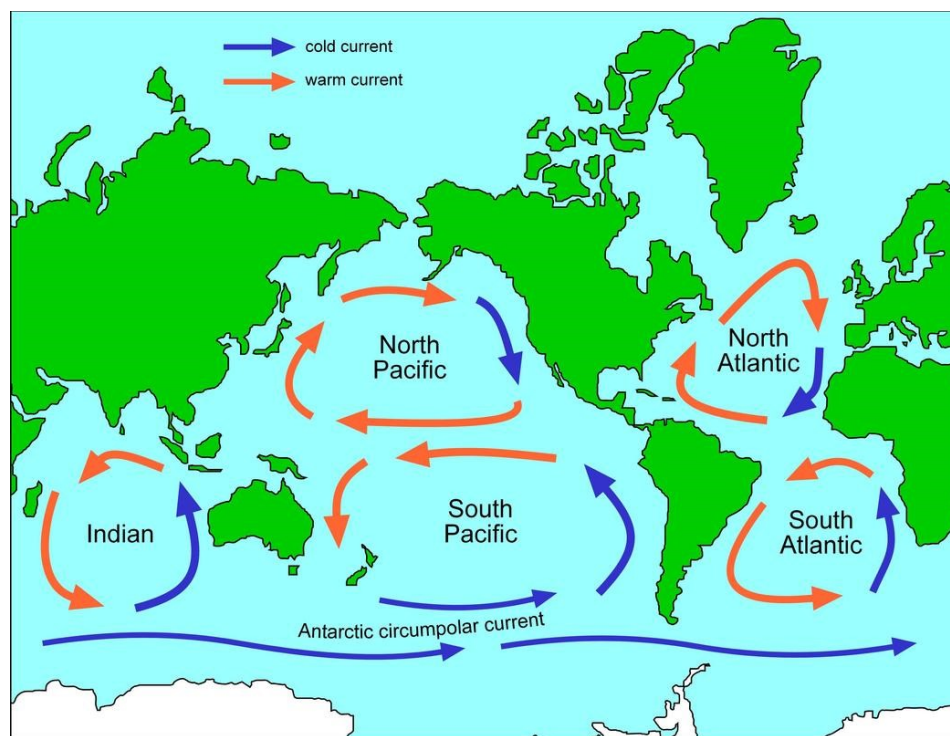


Figure 3. Map of the general location of the five ocean gyres (Ocean Motion, 2022).

4.2 Vertical Transport

When analyzing the overall pathway of microplastics in the marine environment, vertical distribution throughout the water column is just as critical to discuss as the horizontal transportation of plastic particles. Plastic pollution at the surface of the ocean may sink through the water column, as suspected by the presence of microplastics in deep-sea sediment. An understanding of why or how this happens is still not well understood (Kaiser et al. 2017). Due to the natural buoyancy of most polymers, the majority of plastic pollution that ends up in the ocean is confined to the water surface in one of the five gyre currents. Any additives present in a polymer may also contribute to the high buoyancy of plastic debris. When plastic is broken down into a microplastic and undergoes various chemical degradation pathways, the density of the polymer increases. This change in density results in the sinking of plastic particles throughout the water column of the ocean. Along with this reasoning, natural processes caused by the Earth's rotation, particularly Ekman transport, provides further understanding to how microplastics are vertically distributed in the marine environment.

4.2.1 Changes in Density and Biofouling

For many types of plastic, especially in PP and PE, chemical additives are incorporated into its molecular structure to strengthen the durability of the plastic and may also be the cause of increasing the buoyancy of plastic debris (Andrady, 2017). When these chemically altered plastics are in the marine environment, any additives present in the polymer are likely to be dissolved and leached into the surrounded water. This form of additive removal results in the decrease in buoyancy of the plastic particle, increasing its density causing it to sink below the

surface of the ocean. Understanding the impact of adding and removing chemicals to a polymer and changing its density provides insight into this process.

The occurrence of fouling by biodegradation also affects a microplastic by increasing its density. Biofilm is the outcome of fouling, which is the accumulation of organic matter on a plastic particle. When the additional mass of biofilm is added to a biodegraded microplastic, the overall density of the microplastic exceeds the density of seawater, causing it to sink (Kooi et al., 2017). Aggregates, or floating collections of organic matter during algal blooms, are vessels for transporting phytoplankton across the ocean, and now microplastics that are biofouled and imbedded in these aggregates are transported as well (Long et al., 2015). Depending on the original density of the polymer and any additional mass from the presence of biofilm, microplastics are able to sink through the water column, ultimately reaching the ocean floor (Kowalski et al., 2016). Because many microplastics are transported by floating phytoplankton aggregates as well as geostrophic currents, it is not uncommon for microplastics to be found within abyssal-depth sediment. This is due to increase in density of microplastics by biofouling when particles exist within aggregates, resulting in sinking particles. The formation of ocean gyre garbage patches of plastic material in the middle of the Earth's oceans that is inevitably biofouled or chemically altered, provides evidence towards how microplastics reach the ocean floor at great depths.

4.2.2 Ekman Transport

Just as geostrophic currents most likely transport microplastics and plastic waste horizontally across the ocean, Ekman transport is believed to be another process that distributes microplastics vertically throughout the water column. The Ekman transport phenomenon occurs

due to the Coriolis effect when a net movement of water is perpendicular to the direction of wind flow, creating a spiral current from the surface of the ocean to the ocean floor. When frictional forces of wind are matched with the Earth's rotation, the Coriolis effect takes place resulting in the formation of an Ekman spiral. In terms of Ekman transport occurring in the Northern Hemisphere, when wind currents meet with surface water, the direction of surface water flow is 45 degrees to the right the direction of wind. Another 45 degrees to the right of the surface water flow direction, there is another layer of water which flows even further right. This is an ongoing occurrence due to the Coriolis effect depicted in Figure 4, resulting in the formation of currents in a spiral appearance throughout the water column. If this were to take place in the Southern Hemisphere, the direction of net water movement would be to the left of the wind current direction.

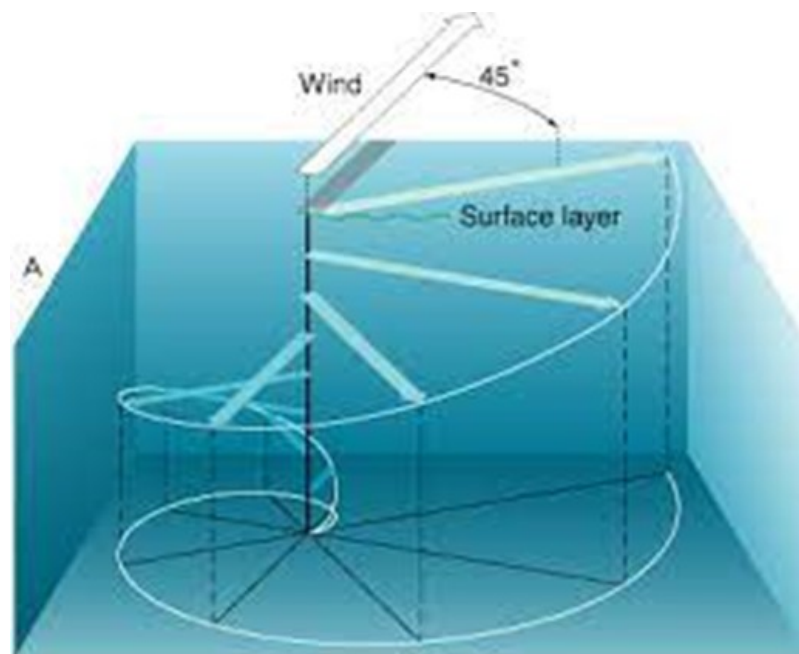


Figure 4. The formation of an Ekman spiral 45 degrees to the right of wind flow when occurring in the Northern Hemisphere (Lindstrom).

When microplastics located at the surface of deep-sea areas are within the pathway of an Ekman spiral, it is likely that it will be transported vertically. The spiral effect of Ekman transport currents can easily pull microplastic particles down towards the ocean floor, where sediment contamination by microplastics takes place (Onink et al., 2019). The Ekman transport mechanism via the Ekman spiral may be a major component in this vertical transport of microplastics throughout the water column.

5 Sediment Contamination

There is still little understanding on how exactly microplastics are transported throughout the water column and deposited on the ocean floor. Because of this, studies done by sedimentologists and environmental scientists to extract microplastics from seafloor sediment are becoming more prevalent and provide evidence to elucidate how vertical transportation occurs. As previously discussed, Ekman transport and geostrophic currents are major factors in the transportation of plastic debris and microscopic particles across the ocean and give way to understanding how these particles are capable of reaching the seafloor. Biofouling is one process which most likely is the main reason for sediment contamination, however, researchers are eager to learn more about this ongoing question in environmental science. The following section focuses on a handful of studies aiming to extract microplastics from both the water column and seafloor sediment, and the methods and techniques used to identify the types of polymers collected.

5.1 Methods of Sample Collection

Throughout each of the research papers used for this study, there were two main methods used for collecting samples for microplastic testing and extraction; water sampling and sediment sampling (Prata et al., 2017). Water sampling is performed by towing and hauling nets of varying sizes throughout the ocean water being tested. Neuston nets are mainly used for collecting planktonic organisms within the first 10cm of the water column by skimming the surface of the water. Because plastics are overall low-density and buoyant materials, neuston nets can easily remove any debris and plastic particles along the ocean surface for further testing. Smaller mesh sizes are ideal as they can collect higher concentrations of microplastics of varying sizes.

However, due to these small mesh sizes of neuston nets it is very easy for them to become clogged with organic material and debris. To prevent this, neuston nets are towed at low speeds. Bongo nets are much larger and capable of reaching greater depths throughout the water column, making them ideal for collecting microplastics that may have been degraded chemically or biofouled causing its initial density to increase. A majority of the studies deployed a flow meter attached to the nets to estimate the volume of water sampled (Prata et al., 2017).

Along with collecting samples from the water column, sediment sampling is completed as well. The use of large vessels is needed in order for equipment capable of reaching the ocean floor to be used. When sediment sampling was done, typically of the top 1-5cm of sediment to be collected, it was more likely that higher concentrations of microplastics were found compared to within the top 10cm of sediment. Concentrations vary greatly depending on environmental factors such as whether a location has high tidal ranges or if there is a large output of primary and secondary microplastics (Prata et al., 2017). Regions with high concentrations of microplastic contamination in sediment are located along continental shelves or lie centered below accumulation zones, or gyres (Van Cauwenberghe et al., 2013). It is rare that microplastics have been found at or beyond the continental margin, yet few studies have been done in these areas. Mechanical factors like wind and currents determine where microplastics in the ocean will be deposited, so sediment sampling is not always successful in finding microplastics.

5.2 Separation Techniques

In order to separate microplastics from sediment and water samples for testing, there are two basic techniques used; filtration separation and density separation (Prata et al., 2017).

Filtration separation works to reduce the volume of the sample to ensure that every particle can be identified and extracted. This step is done by using smaller mesh size nets and sieves to decrease the size of the sediment sample without losing any microplastic contaminants. The use of small mesh sizes to remove larger sediment particles results in a supernatant of a sample solution, the liquid above the solid residue of a mixture as a result of a separation procedure, along with any remaining plastic contaminants. This is then further separated to fully extract microplastics present in the sample. Water samples are typically sent through filtration sieves ranging in sizes from $0.3\mu\text{m}$ to $200\mu\text{m}$ (Prata et al., 2017) to remove any unwanted organic debris or sediment that may have floated into the path of the water sampling collection method.

Once reduction by filtration has been performed, density separation is then used for further analysis. A salt compound is typically added to the filtered sample along with ultrapure water to increase its initial specific density, resulting in the less dense microplastic particles becoming buoyant and float for simple extraction (Prata et al., 2017). The most common salt used in density separation is sodium chloride (NaCl). NaCl is a cheap, non-toxic salt that increases the initial density of a solution when added (Constant et al., 2021). Other compounds which have been used for density separation include zinc chloride (ZnCl_2), sodium iodide (NaI), and calcium chloride (CaCl_2) (Bellasi et al., 2021). NaCl has reported a recovery rate of roughly 63% with great variation in recovery rates throughout numerous samples. Although NaCl may not produce the best outcome for contaminant concentrations collected, the other salts previously listed are much more costly and hazardous to use. The dangers of using these salts include eye and skin irritation or burning, damage to organs due to prolonged exposure to the compound, and toxicity to marine life if used in marine locations. Due to these hazards, researchers have elected to use NaCl for completing the density separation step of the extraction process.

In some instances, using sucrose ($C_{12}H_{22}O_{11}$), or table sugar, along with the NaCl salt to ultrapure water has been effective to produce a denser solution for density separation use (Bellasi et al., 2021). The denser the solution is, the higher the concentration of extracted contaminants. Bellasi et al. (2021) used sucrose in addition to NaCl during the density separation step for microplastic extraction from various samples. When preparing a sucrose and NaCl solution, NaCl is first dissolved in ultrapure water, which has a density of $1 \times 10^{-6} \text{g/cm}^3$, to create a fully saturated solution. Enough NaCl must be used to fully dissolve in 100g of ultrapure water at 20°C . To this saline solution, 100% (weight/volume) of sucrose is added. This achieves a density separation solution with a density of 1.3g/cm^3 (Bellasi et al., 2021) and this is then added to the sample being tested.

With a high-density solution, more microplastics within the sample can be removed from the supernatant of the mixture (Bellasi et al., 2021). Because some polymer particles may remain denser than that of the sucrose and NaCl solution, it is possible for microplastics to remain within this supernatant layer of the separated mixture. If this is the case, the supernatant is collected for further filtration and processed through another application of density separation.

5.3 Polymer Identification

From this multiple step process, Bellasi et al. (2021) were able to collect hundreds of microplastic particles from both water and sediment sampling and identified five of the six most common polymers from these samples. Raman spectroscopy is a technique used to determine the chemical structure and molecular bond of a material (Lots et al., 2017) by measuring the interaction of light and the chemical bonds in the material. A non-destructive laser light source is projected onto the collected microplastics that are then analyzed for identification. By measuring

the interaction between light and the microplastic, spectra of frequencies are recorded and then compared with the known frequency spectra of polymers. These spectra are ranked with how well they can be matched with a known polymers' spectra to determine the type of plastic polymer a microplastic is. By identifying the polymer type of the particle, scientists can figure out where the microplastic may have originated, depending on information known about what types of polymers are used or released into the environment in certain locations across the globe (Lots et al., 2017).

In the study done by Bellasi et al. (2021) the five common types of polymers were identified as polypropylene (PP), polyethylene (PE), polystyrene (PS), polyethylene terephthalate (PET), and polyvinyl Chloride (PVC). PP particles with a density of 0.91g/cm^3 , PE particles with a density of $0.917\text{-}0.965\text{g/cm}^3$, and PS particles with a density of $1.04\text{-}1.1\text{g/cm}^3$ were easily extracted due to their low densities relative to the high-density solution, meaning they were buoyant. Two other polymer types were identified having densities greater than the sucrose and NaCl solution. These denser particles were difficult to extract, calling for a repetition of the separation steps (filtering and density separation), and included PET with a density of $1.37\text{-}1.45\text{g/cm}^3$ and PVC with a density of 1.58g/cm^3 were identified (Bellasi et al., 2021).

6 Impact on Life

Although the presence of microplastics in the marine environment alone is of great concern, they have impacted more than just ocean water. Life is being directly impacted by plastic pollution and microplastics, especially marine and coastal wildlife. It is difficult for wildlife to differentiate between prey and plastic pollution. Ingesting plastic can lead to multiple health issues and because of the immense accumulation of plastic waste on beaches and in ocean water, these health concerns only grow larger for marine animals. Wildlife, however, are not the only life on Earth being impacted by microplastics and plastic pollution. Humans are now exposed to the dangers of microplastic due to seafood consumption and poor water filtration.

6.1 Marine Life

Marine wildlife is impacted by the plastic pollution and microplastics by either entanglement or ingestion. In 1997, there were at least 297 marine species that were affected by plastic waste (Derraik, 2002), 44% being sea birds. Sea bird species typically find their food supply at the ocean surface where small fish and other organisms can be easily caught. Microplastics are found in this upper level of the water column, and often within zones of phytoplankton concentrations (Andrady, 2017). It is not uncommon for the fish that reside in this surface layer to prey on these phytoplankton, often resulting in the simultaneous ingestion of microplastics. Sea birds that prey on fish at the ocean represent a large percentage of the species impacted by plastic waste. In 1997, eleven sea birds of the same species were analyzed along the coast of the North Pacific Ocean where eight of the eleven birds studied had microplastics within their stomachs (Derraik, 2002). When plastic enters the stomach of an organism there is a

decrease in stomach volume. This means meal sizes are reduced, resulting in the malnutrition and starvation of many species of seabirds.

Various species of fish, particularly those residing along the ocean surface, have been found with microplastics in their gut and trapped inside their gills. The accumulation of microplastics in gills interferes with the amount of oxygen the organism can take in, causing several other health concerns due to poor oxygenation (Kontrick, 2018). Microplastics within the gut of an organism poses a risk for digestive diseases and poor feeding habits. During digestion, any chemicals or additives within the polymer of the plastic particle can be leached in the organism. Long term effects of this occurrence can be reproductive issues and infertility of wildlife, along with growth abnormalities (Kontrick, 2018). There is no denying that microplastics have entered the food web of entire ecosystems within the ocean, which may also be a contributor to why there have been records of loss in biodiversity of various marine environments around the world.

6.2 Human Life

Although the long-term effects microplastics have on humans has not yet been documented, there have been recent studies that acknowledging that humans are now being impacted by plastic pollution and microplastic particles. As marine life has been found to ingest plastic particles, microplastics are readily found in seafood (Kontrick, 2018) and marine products often consumed by humans. Along with this, water filtration systems work to provide clean and sanitary water for household consumer use. There have been occurrences where household water supplies have been tested for contaminants, with microplastics being a leading concern. It is still

unknown whether humans have ingested microplastics, but it can be assumed this is the case as it has been confirmed that microplastics can pass through these filtration systems (Kontrick, 2018).

7 Policies Against Plastic Waste

Over the past few decades, the topic of microplastics and plastic pollution in the marine environment has quickly gained popularity yet there is still a growing concentration of plastic waste worldwide. Reusable plastic containers and bottles have become readily available to consumers inevitably become no longer usable, adding to the increasing amount of environmental pollution. This ongoing concern is acknowledged by governmental authorities on a global scale. Smaller scale legislation has become more prevalent across multiple nations providing possible solutions for preventing the consumer level production of plastic waste, with the hopes of greatly decreasing the overall amount of plastic that enters the ocean.

7.1 Worldwide Plastic Legislation

The manufacturing and fishing industries are responsible for nearly 60% of the world's plastic pollution in the ocean combined. The establishment of the 1972 Convention of the Prevention of Marine Pollution by Dumping Waste and Other Matter (Derraik, 2002), placed a ban on commercial or industrial direct disposal of plastic waste from production into waterways and oceans. By recognizing that transportation ships were another leading cause of plastic pollution in the ocean, the Protocol to the International Convention for the Prevention of Pollution from Ships (MARPOL) came into effect in 1978 (Derraik, 2002). Annex V of MARPOL is a key international authority which controls this protocol by restricting the discharge of garbage at sea and bans sea disposal of plastics such as ropes, garbage bags, and packaging containers (Derraik, 2002). By 2002, 79 countries had ratified the Annex V with many others quickly pushing for consent to implement the protocol into their national legislation. On a national level in the United States, the Marine Plastics Pollution Research and Control Act was

established in 1987 which worked to authorize ships of the disposal plans of their plastic garbage (Derriak, 2002). The biggest concern for protecting the marine environment from additional plastic pollution was not only having the legislation previously mentioned but also the ability to enforce these laws over an area as large as the world's oceans.

7.2 Solutions for Consumer Plastic Use

The everyday consumer can help decrease the amount of plastic pollution in the ocean in many ways. Recycling of most plastics can be done to prevent further plastic from being produced and added to the environment, although recycled materials are often costly due to it being difficult to clean already used plastics of contaminants and sorting different types of plastics for repurposing (Moore, 2008). Biodegradable options instead of plastic items are quickly becoming more prevalent around the world. These products are composed of organic material, allowing them to breakdown naturally in the environment when they are disposed. Bans on consumer plastics use are placed on certain stores and locations where plastic packaging may be unnecessary. This includes plastic shopping bags, cups, or take away containers, as they are typically used once and thrown away (Moore, 2008).

Beach activity is another major source of plastic pollution that directly enters the coastal and marine environment. Authorities of beach locations can push for beach goers to keep the area clean by picking up any trash or debris that is likely to be left behind. Beach cleanups are organized all over the world to keep coastal areas free of plastic trash brought by beach goers or by litter that may have been transported from inland sources (Moore, 2008). Beaches allow for the direct input of plastic pollution into the marine environment, making beach cleanups critical to protect the ocean from plastic waste.

8 Conclusion

The presence of microplastics in the marine environment has become an ongoing issue across the world. It is no surprise that plastic waste left behind by humans exists within marine ecosystems, posing as a hazard for wildlife, and inevitably humans as well. The ingestion of plastic particles and entanglement within plastic pollution threatens the lives and safety of marine life. Chemical additives used in the production of plastics poses even greater health risks for marine life if ingested and absorbed by the organism. Using proper disposal techniques of plastic products and packaging does work towards stopping plastic debris from reaching the ocean, however, the direct disposal of plastic waste and manufactured microplastics such as those used in cosmetics, are leading sources of plastic pollution in the ocean.

It is important for research regarding plastic pollution in the ocean and the impact of microplastics to be conducted in order to continue the discussion of environmental protection, especially in the marine environment. Management of plastic waste is a major factor of considering the future health of the Earth, yet the current use of plastic products can be altered as well. Businesses have recently pushed for the use of paper or reusable packaging products in an effort to decrease the amount of plastic. Consumers can educate themselves to become more aware of sustainability and ways they can live environmentally friendly lifestyles. Plastic is a material that always will be used despite its negative effects on the planet, however, switching to more sustainable ways of living and reducing the usage of plastic products should be acknowledged worldwide.

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