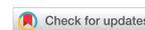


Review

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The prevalence of microplastics on the earth and resulting increased imbalances in biogeochemical cycling

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Abstract

The biogeochemical cycles are responsible for the constant transfer and transformation of matter and energy between the biosphere and the other active reservoirs of the planet. During the progress of a biogeochemical cycle, a series of molecular species (ecological “nutrients”) are constantly transferred and chemically altered. Plastic, a new material, has now begun to participate in the biogeochemical cycles. More than just participating, microplastics are interfering with the normal flow of these processes insofar as they can block the transfer of some elements and serve as a shortcut for others. These new materials can increase the bioavailability of pollutants and thus interfere with physiological activities. The results of this interference have not yet been fully evaluated, but in view of the universal presence of these particles in the most varied ecosystems of the planet, urgent measures



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must be taken to mitigate the negative effects of this invasion. The present review seeks to establish a global view of the distribution of microplastics around the planet and their impact on the main biogeochemical cycles, thus emphasizing the need for the development of adequate management and remediation strategies in the coming years.

Keywords: Pollutants, nutrients, organic matter degradation, microplastic particles, conglomerates, mineral cycling

INTRODUCTION

Planet Earth can be considered a closed system, where all its constituent chemical elements are trapped by gravity and distributed in several pools among the existing global ecosystems^[1]. However, in response to heat fluxes, the elements are constantly cycling between the different compartments^[2]. The fluxes of chemical elements such as carbon, oxygen, nitrogen, phosphorus, etc., among different Earth reservoirs, compose the biogeochemical cycles^[3], in which biological, geological, and chemical elements are all involved. These fluxes run through compartments present in the most varied spheres of our planet, including living to non-living, from air to land and sea, and from soils to biosphere; they can impact plant productivity as well as the speciation and resulting bioavailability of potentially toxic elements^[4].

Biogeochemical cycles and compounds sustain the dynamics of the Earth. This equilibrium is based on the capacity of the elements to transit through extremely diverse pools. Microorganisms, being able to recycle carbon, nitrogen, phosphorus, sulfur, and other elements, thus play a key role in many biogeochemical cycles [Figure 1]^[5]. The metabolism of microbiota sustains the most important biogeochemical cycles on the planet, especially the production of oxygen, which allows aerobic life and consequent biological transference of carbon to biological reservoirs as biomass^[6].

Throughout their existence, human beings have caused a series of disturbances in the natural balance of the planet. Following the industrialization of human society, various contaminants began to be discharged into the environment, generating direct impacts on ecosystem balance^[7-9]. The global balance of carbon and other nutrients is increasingly affected by human activities^[10] insofar as they accelerate or block the processes of transfer of elements between the different Earth compartments, as well as creating new transfer vectors and “shortcuts”. Keeping in mind the magnitude of microplastic particles in the marine environment, this may significantly modify the route and impacts of contaminants in the environment^[11]. It is within this context that microplastic is discussed in the present article.

Traditional plastics are a group of synthetic polymers produced from hydrocarbons to which various chemicals are added to define the final properties of the product, such as elasticity, color, resistance to microbial growth, etc. During degradation, plastic is broken down into small particles, known as micro or nanoplastics (plastic particles ranging from 1 μm to 5 mm), that currently represent the most abundant and ubiquitous class of anthropogenic wastes in marine and freshwater ecosystems^[12]. The sudden appearance of these wastes meant that the Earth was not prepared to deal with such complex compounds through its biogeochemical cycles. There are few groups of microorganisms able to rework, and thus recycle, the components of the plastic matrix, leading to its accumulation in many ecosystems.

The plastic matrix has an extremely versatile nature, being able to attract and sorb other contaminants, thus changing the trajectory of these potentially toxic compounds in the natural environment^[13]. This may intensify their bioavailability and toxicity to other levels of the trophic chain^[14,15]. Thus, only through the understanding of its nature and behavior in a global way will it be possible to effectively manage and

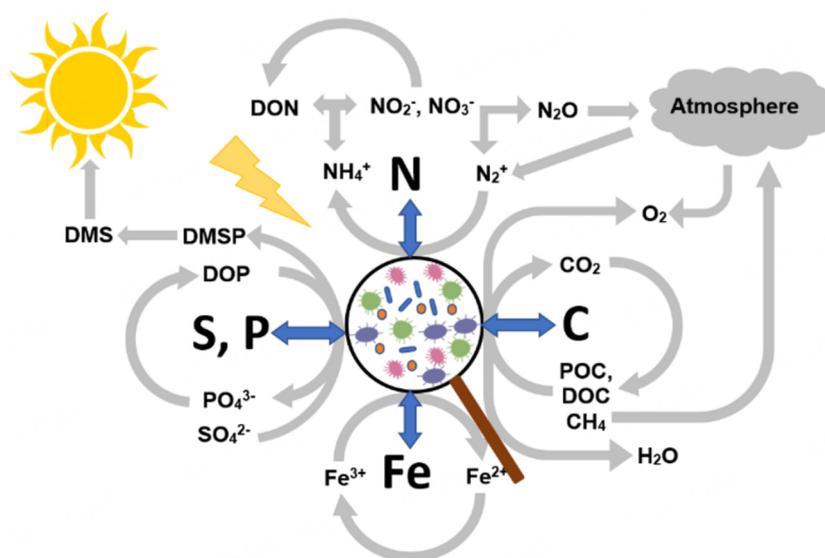


Figure 1. Biogeochemical cycles in the sea and the role of the microbial food webs.

attenuate the impact of plastic pollution^[16]. Thus, this article presents the potential impacts already observed in the main biogeochemical cycles in order to allow the projection of the impacts on the chemical balances between the different geochemical compartments of the planet Earth.

MICROPLASTIC: A NEW BIOGEOCHEMICAL CYCLE?

Discovered during the 1930s and produced on a large scale from the 50-60s, plastics now play an important role in the daily lives of human beings. The properties of these man-made long-chain polymeric materials, such as strength and durability, together with flexibility, thermal and electrical insulation, corrosion resistance, and low cost, have made them important in the production of a wide diversity of items such as clothes, cosmetics, tools, paints, appliances and others^[15,17]. Additionally, these same characteristics represent a threat to human beings in the medium and long term; the refractory nature of plastics offers great ecotoxicological potential. Because of improper management and disposal practices, plastic residues are found throughout the planet's ecosystems. The action of environmental agents promotes deterioration, producing plastic fragments that are classified as microplastics when their size is < 5 mm^[17]. They are ubiquitous in all global ecosystems^[18] and their special characteristics allow transference even to remote sites^[19].

Exposure to and bioaccumulation of these particles can impact human health^[15] as they can adsorb toxic chemicals^[20] and bioaccumulate in food and tissue^[21,22]. Microplastics can also alter and negatively influence soil microbiomes^[23,24] and impact physiological and resulting ecological processes^[22,25].

The terrestrial environment represents the main source of plastic microparticles since this is where the processes of industrial production, utilization (consumption) and waste accumulation and treatment are concentrated^[26-28]. Plastic microparticles are released from products that contain them, such as cosmetics and abrasives^[29,30], from wastewater sludge^[31,32] and many other sources. Such industrially produced microplastic (MP) particles are classified as "primary microplastics"^[33]; they do not result from the breakdown of macroplastics.

During the lifetime of a larger plastic item, however, it faces a number of factors that contribute to its wear, resulting in the release of small particles, which can be classified as secondary microplastics, into the environment. One example is the release of plastic microfibers from fabrics during washing^[34]. These may be transported by wind and water, from soils via surface runoff, and through rivers and canals^[35,36]. They may accumulate in seas and oceans or in transitional locations. As they travel, they are continually subjected to deterioration by physical^[37], chemical^[38,39], and biological^[40] degrading agents like UV, temperature, buffeting actions of wind, waves and currents, acids and biological enzymes. This class of plastic particles, resulting from the deterioration of primary MPs or breakdown of larger pieces, is called “secondary microplastics” [Figure 2].

MP accumulations obviously vary by the location, polymer nature and how far they are from the source. The dynamics of distribution and abundance, the factors that dictate MP distribution, and the transport fluxes that could affect the distribution are still unclear. It is important to understand the nature and distribution dynamics of MPs in global environment pools to allow us to project the ecotoxicological threats and devise and offer appropriate management strategies to minimize their impact in natural environments.

MICROPLASTIC DISTRIBUTION THROUGH THE GLOBAL POOLS AND POTENTIAL ECOSYSTEM TOXICITY

MPs have been recorded in diverse environmental compartments, from soils to aquatic systems^[41,42]. The following is a summary of potential sources and flows through each compartment.

The terrestrial compartment

Effective sources of MPs for the terrestrial ecosystem include the transport industry, e.g., traffic and vehicle tire abrasion^[43-45], cosmetics and cleaning products^[23], clothing and textile washing^[34,46], automobile and architectural paints^[47], among others. Consequently, urban dust and its runoff, containing all the residues mentioned above, are important sources of microplastic contamination for the terrestrial environment^[48,49].

Agricultural practices can also contribute through improper disposal of wrapping and bale twine, and sewage sludge applied to agricultural lands^[50]. MPs can be transported vertically through the soil interstitial spaces to the deeper layers^[51]. Along with mismanaged waste and littering, plastic accumulation within the terrestrial environment acts as a source for other ecosystem pools^[52].

The aquatic compartments

After deposition on the soil surface, the plastic microparticle can be transported horizontally to aquatic ecosystems through surface runoff. It can also be a viable route to aquifers or groundwater systems^[53,54]. It has been suggested that groundwater contamination by microplastics [Figure 3] is mainly linked to anthropogenic activities, such as agriculture, fishing, wastewater treatment, and family activities aboveground^[55-57].

Due to the multitude of freshwater ecosystems with differing hydrology, chemistry, and biome, as well as their surrounding watershed and land-use patterns, MP pollution in aquatic freshwater ecosystems is very complex. In the same way as the atmosphere and other compartments, freshwater environments potentially work as both receivers and diffusers of plastic pollution^[42,58]. For example, rivers may have significance in the transfer of plastic from land to the adjacent sea^[52,59]. It has been projected that rivers and estuaries release 0.47-2.75 million tons of plastic into the sea annually^[59]. On the other hand, significant concentrations of MPs have been recorded in ponds and lakes around the planet^[60-62]. In contrast to the riverine sites, however, lakes and lagoons, being more confined and thus presenting minor water transport competence, tend to

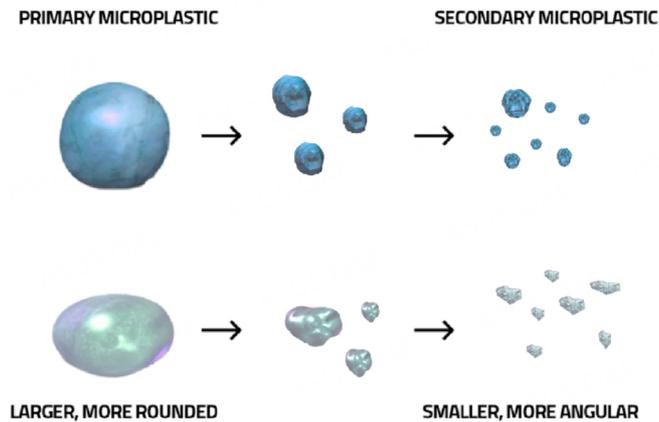


Figure 2. Degradation of pellets (Primary Microplastics) and resulting changes in appearance.



Figure 3. Microplastic particles found in Marica City Groundwater (Rio de Janeiro/Brazil) (Source: own material).

concentrate plastic in the sediment without further exportation to the surrounding sea and can thus more readily concentrate plastic over time^[63].

MP pollution in the salty marine environment has received more attention than in other ecosystems. First, because MPs are frequently recorded in high levels in both the water column^[64] and in the bottom sediments^[65], where they can be available to the marine biota, and secondly, since seafood is a primary source of protein for a significant percentage of the world's population^[66], MP contamination in marine ecosystems represents a potential human health risk^[15]. Sources of MPs for the oceans include terrestrial runoff^[67], plastic industrial wastes^[68], abandoned fishing nets^[69] and many others. Anthropogenic activities on the coasts, including fishing, aquaculture^[70] and tourism, also represent important sources of MPs for saltwater environments.

Marine waters have specific features, such as their physicochemical characteristics and extremely variable hydrodynamic flows^[64,65,71], that impact the diffusion dynamic of MPs. In addition, the salt content of marine water may be expected to influence MP water column distribution (buoyancy and sinking properties), fate, diffusion dynamic in marine environments and, finally, the bioavailability of MPs to marine biota^[72]. MPs are composed of a variety of polymers with varied molecular structures^[73], resulting in properties that determine the action of saline water on the particles. For example, the transport of MPs through the water column is influenced by the settlement of organic particles from the surface to deeper layers ("marine snow"), enabling the contamination of deeper pelagic environments down to the benthic communities^[74,75].

The sea bottom settlement stability of MPs can be impacted by deeper thermohaline currents^[65], which may allow their return to the global plastic cycle.

It is thus accepted that the ocean environment is the depository of MP, with terrestrial and freshwater fluxes being important contributors to marine deposits^[52]. Aquatic sites like oceans represent not just deposits of plastic microparticles, but effective sources of plastic back to the atmospheric pool via wind-driven sea spray and the bubble burst ejection^[76]. Aquatic MPs hotspots may thus act not just as a final deposit of these pollutants but also as a source of MPs back to the atmospheric “pool” and further to terrestrial sites. Hence diffusion of plastic microparticles through several ecosystem compartments impacts the distribution of pollutant molecules through soil and water, just as carbon, oxygen, nitrogen, and other elements participate in their environmental and biogeochemical cycles^[77].

The atmospheric compartment

Regardless of features such as shape, size and molecular structure, MPs generally present low density, small size, and high surface area, enabling easy spread through the air^[78-80]. Daily human littering activities linked to inadequate management, unconfined litter storage, and release from landfill sites are also potential atmospheric MP sources; these have been shown to be deposited with precipitation even in remote sites such as the French Pyrenees^[81] and the Alps^[82,83]. MPs are indeed subject to long-range transference and atmospheric deposition^[84] from urban areas to remote locations^[81,85-87]. The atmospheric pool acts to link the processes, influencing the flux and retention of MPs in the environment [Figure 4]^[88].

THE DETERMINING FACTORS FOR MP DISTRIBUTION IN THE GLOBAL ENVIRONMENTAL COMPARTMENTS

The distribution of MPs is directly associated with their physical features. Their diffusion in the environment is directly linked to the mechanical transport associated with wind flows and water currents; it is coherent to suggest that the different shapes of MPs may influence their transport through the environment. For example, plastic films can vary in thickness and size and thus have a greater surface area for atmospheric entrainment than fragments of the same mass^[76]. Thus, it has been shown that fibers and fragments are the dominant MP shapes in the atmosphere and seawater, beach sediments, and freshwater^[89-91]. Comparison with MPs of aquatic and sedimentary environments^[41,91] suggests that atmospheric MPs are much smaller. Finally, plastic particle size and shape are determinants of bioavailability and environmental fate^[92,93]. Certain MP shapes or sizes may result in a greater impact on living organisms, with smaller, more angular particles passing more easily through membrane barriers than particles with smoother surfaces^[73,94], also allowing the easier entrance of associated contaminants.

Not only shape and size but also MP composition impact particle dispersion in the environment. Different polymers have different densities^[94], which affects their pathways through the environmental compartments. Less dense polymers are more common in aqueous and atmospheric compartments^[84].

MPS, ENVIRONMENT, AND TOXICITY: THE INTERACTIONS

Plastics are polymers formed from resins. Polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), polystyrene (PS), and polyethylene terephthalate (PET) make up approximately 90% of the total plastics in common use^[95]. Chemical additives such as plasticizers, stabilizers, antioxidants, pigments, and flame retardants are commonly added to the formula to improve characteristics like resistance and flexibility^[96,97]. The plastics industry uses small plastic pellets as feedstock. These are tiny plastic granules that are melted down and remodeled into the required shape; thus, they are an important raw material for many industries around the world. Nowadays, however, improper transport management and irregular disposal in the environment have resulted in worldwide pollution by these primary MPs.

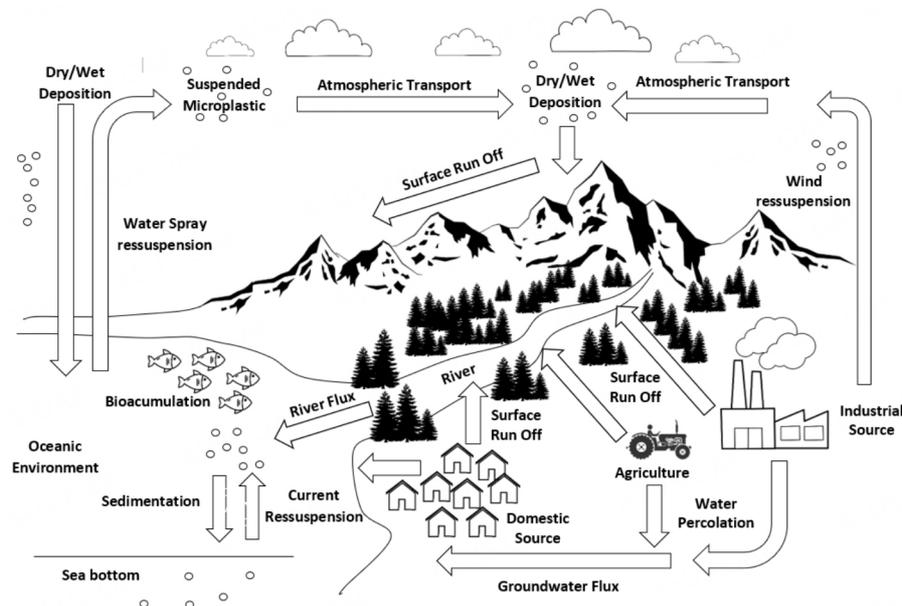


Figure 4. Conceptual Model of Microplastic flux through Global Environment Pools.

With a highly varied composition, MPs can sorb a large group of contaminants. Various mechanisms are involved, such as physical adsorption, pore filling, surface complexation, and electrostatic attraction^[98], as well as agents like UV radiation, microorganisms, humidity, and other environmental factors. Certain additives, such as pigments, can affect sorption capacity. Antunes *et al.*^[99] suggested that black-colored MPs are more likely to contain polyurethane, which may contribute to higher sorption. Fisner *et al.*^[100], on the other hand, reported that lighter-pigmented particles adsorbed lower molecular weight hydrocarbons, while darker particles contained higher-weight PAHs. Polymer density has also been suggested to influence pollutant sorption; higher-density MPs may carry lower concentrations of pollutants such as PAHs and PCB^[101-103].

As explained previously, secondary MPs result from the degradation of the primary class, pellets, or larger manufactured plastic items, by physical and chemical environmental agents like UV, mechanical abrasion, and microbial action. These modifications can affect pollutant sorption capacity^[100-106], and hence contaminant carrying ability. Naturally, during plastic aging and degradation in the environment, MP characteristics like porosity, density, and roughness will change^[107]. After degradation, the smaller granulometry and corresponding higher surface/volume ratio increase pollutant sorption^[108]. Chemical weathering and UV action modify the functional groups on the particle surface, transforming both polymer chain and additives chemistry by oxidation and chain scission of polymers^[17]. This increases the ability to attract environmental pollutants, including hydrophobic and hydrophilic organic pollutants, endocrine disruptor compounds, and heavy metals^[104,109]. The effect of MP degradation on the pollutant sorption capacity does not depend only on the size or degree of degradation. The information available in the literature is very controversial. Some authors support the idea that the adsorption capacity increases with aging^[104,109], while others^[106] reported that weathered or aged MP had lower pollutant sorbing capacity. In fact, the impact of MP degradation on contaminant sorption depends on several variables, including the type of polluting compounds and microplastic, and the stage of chemical modifications or resulting interactions over time.

Some types of polymer composition confer the ability to sorb hydrophobic pollutants^[110]. In aqueous or solid ecosystems, MPs are always recorded as part of a mixture or diverse suite of chemical compounds^[73], reinforcing their ability to attract organic chemicals and trace metals from the adjacent environment^[97]. This occurs because hydrophobic chemicals are attracted to the neutral spots on the MP surface, while hydrophilic or charged compounds establish electrostatic bonds with the negative areas on the particle surface^[110]. The nature of the plastic matrix thus has an important and versatile effect on the accumulation of pollutants.

Apart from the composition of the plastic polymer, the sorption of polluting molecules also depends on the physical and chemical nature of the environment, as discussed in the following paragraphs.

Organics content

The presence of organic matter can alter the in-situ sorption capacity and distribution of marine MPs^[92,111,112]. When the level of organic compounds in the ecosystem is low, adsorption occurs as a result of the strong interactions between the forces on the surfaces of the MP particles. When the organic content is high, absorption prevails, as there is a larger volume for the molecules to settle^[113,114].

pH

This environmental factor has attracted more attention with the advent of global warming. The marine environment has passed through an acidification course, which could increase the sorption process of certain aquatic contaminants. Although the pH of oceanic environments is severely buffered to around 8.0, coastal waters can be impacted by pH variations^[115]. In the case of plastic microparticles, fluctuations in seawater pH can change the surface chemical stability of microplastics, stimulating or neutralizing the leaching rate of chemical compounds adhered to the surface. Thus, the PET that is usually classified as relatively safe for the environment could become a threat in different environmental conditions. For example, the attraction of the endocrine disruptor tylosin to PVC is stimulated after the plastic's solubility increases at lower pH; the sorptive capacity of PS and PE for perfluorooctanesulfonic acid also increases Guo *et al.*^[116]. Despite the existing evidence, broader and more detailed data are needed to project the real effects of pH on the sorption capacity of plastic microparticles.

Salinity

Salinity represents the main environmental characteristic that impacts the toxicity of chemicals on biota^[117]. Additionally, it plays an important role in the contaminant adsorption dynamic of MPs. As an example, the adsorption of some pollutants onto MPs was investigated through a controlled assay, in which adsorption was stimulated by changing salinity, altering hydrophobic forces, and the salting-out process^[118,119]. Results suggested that increasing salinity is one of the processes that decrease the adsorption of contaminants on microplastics, although the kinetics depends on the makeup of the plastic matrix.

The chemical patterns in the environment may be a key factor in the attraction of contaminants by MPs; these attractions do not exist only as a function of the physical or chemical characteristics of the polymers, but also of the properties of the surrounding medium. The influence of the age of the plastic and its composition on the attraction of a contaminant are a result of the functional groups existing on the surface of the plastic matrix; the polarity and chemical forces are due to differences in these functional groups affecting polarity or chemical forces such as hydrophobicity over time or across various types of pollutants^[109,120].

THE INFLUENCE OF MICROPLASTIC PARTICLES ON MICROBIAL COMMUNITIES AND

RESULTING IMPACTS ON BIOGEOCHEMICAL CYCLING

The potential impact of microplastic particles (MPs) on biogeochemical cycling and microbial communities has been the focus of much research because of their crucial role as drivers of biological and nutrient balance in various ecosystems^[121-127].

Microorganisms play a crucial role in the trophic pyramid, allowing dead organic matter to be recycled through saprotrophy, resulting in the release and reuse of chemical elements, mainly C, N and P^[128,129]. Thus, MPs influence the microbial oxidation-reduction reactions that represent a basic issue in environmental balance. Despite the lack of information regarding the impact of MPs on the environment, their importance on microbial communities can be discussed under a number of headings, as follows.

Bioinvasion

The MP surface offers unique microhabitats which allow the transportation and diffusion of allochthonous species, which can seriously impact communities in specific environments^[130]. The invasion of exotic species is one of the most to local biodiversity and ecosystem functioning in local environments^[131,132]. There are increasing records of invasive microorganisms, which can modify the functioning of entire ecosystems^[133-138]. Invasive microorganisms can modify these geochemical paths through local disturbance of symbiotic patterns, pathogenicity, or imbalance of local decomposition processes. The transport by MPs of microbial cells and potential allochthonous species can thus upset the pre-established structure of an ecosystem, putting its particular biogeochemical processes at risk [Figure 5]^[139].

Ecotoxicity

MPs can attract, transport and release complex toxic compounds through the ecosystems, affecting local microbial community structure and abundance, potentially impacting biogeochemical cycles [Figure 5]. Some authors showed that the availability of polyethylene (PE) transformed the local microbial community by reducing its richness and raising the abundance of lignin-degrading and plastic-degrading species^[140]. Several other researchers have revealed that MP toxicity can disturb the structure of microbial populations^[24,80,141,142].

Changes of colonization substrate

The imbalance generated in biogeochemical cycles by MPs is mainly concentrated in their impact on the microbial population. In addition to carrying invasive species to other ecosystems or impacting the health of the microbiota through the bioavailability of pollutants, microplastics can also modify soils and underwater sediments by altering substrate characteristics, resulting in ecological succession/replacement [Figure 5]. According to^[130], during the biofouling process, a “protective layer” forms on the surface of the microplastic, allowing the group of organisms dependent on the compounds leached into the plastic matrix to survive in other environments. Thus, the very pre-existence of a plastic substrate in the environment makes it open to bioinvasion from more MP-attached microorganisms, which may impact the biogeochemical processes promoted by the original microbiota.

The impact of MPs on microbial communities may be particularly significant in environments prone to plastics accumulation by urban surface runoff^[143], in situations where waste management is poor^[52] or fails due to overload of the sewage network^[78], or in the vicinity of the wastewater treatment plant outfalls^[144,145]. It is, therefore, to be expected that aquatic environments will be the most subject to MP pollution. Particularly ecosystems such as salt marshes and mangroves, usually located in geomorphologically protected areas, represent extremely sensitive environments since the hydrodynamics in these areas is usually restricted, with the tides as the main source of currents^[71]. Additionally, these ecosystems present typically adapted flora, with aerial roots, for instance, that block hydrodynamic currents, resulting in the

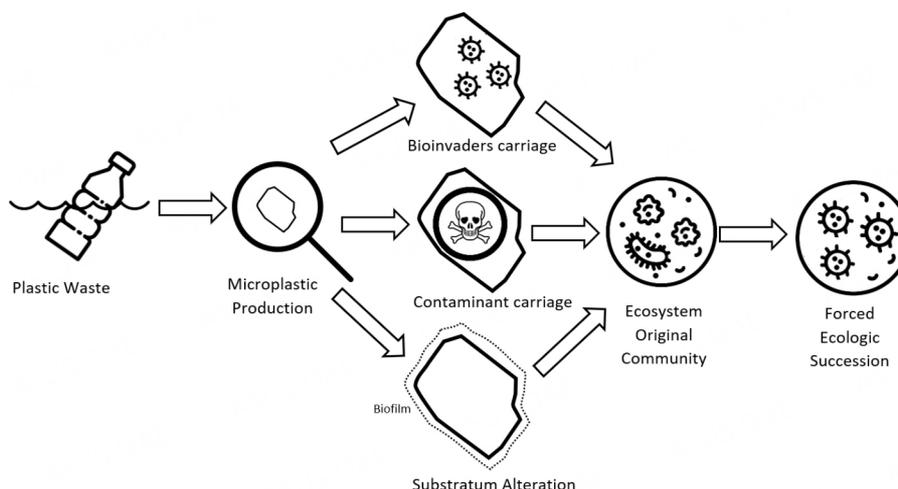


Figure 5. MP microcosm disturbance mechanisms.

accumulation and decantation of fluctuant solids, organic matter (OM) and MPs^[71]. On the other hand, these ecosystems represent highly active areas of OM remineralization and hence biogeochemical cycling, for which sediment bacteria are fundamental.

The diagenetic process starts with the decomposition of the most-labile OM compounds within the oxygenated surface water^[146]. In low-oxygen areas, organic matter is usually degraded through fermentation, denitrification, sulfate-reduction, and methanotrophy^[147]; these reactions are carried out by specific organisms with particular redox requirements.

MPs, mainly microfibers, have been shown to impact sediment quality and health by modifying the microbial community and its resulting biogeochemical activity^[122,148]. For instance, microplastic fibers decrease bacterial enzymatic activity^[149].

In terrestrial environments, carbon and nitrogen recycling is mainly conducted through transformation between vegetation and internal constituents of soil and occurs in the transition zone between the atmosphere and water environment. Abiotic features, such as soil properties and local climatology, as well as biological elements such as microbial communities, animals, and anthropogenic activities, affect the biogeochemical turnover of carbon and nitrogen in the Earth's complex ecosystem^[80,150]. The impacts on the main elements of the biogeochemical cycles are discussed in the following sections.

IMPACTS OF MPS ON THE MAIN BIOGEOCHEMICAL CYCLES

Carbon

The plastic matrix is composed of carbon chain polymers^[151-154]. around 80% of MP composition is carbon^[155] and the scale of plastic production and disposal each year has made it a new element in the carbon cycle^[156]. The plastics industry is directly related to the release of greenhouse gases in all phases of the plastic life cycle, from production to transport and final waste disposal^[151,157]. MP carbon is thus already present in the global soil compartment, although generally representing only a small fraction of total soil organic matter carbon^[155]. This picture may, however, change in the future, since the organic carbon from microplastics is not easily bioavailable, unlike plant residues, and not subject to ready biodegradation^[158]. MPs can negatively impact plant development in several ways; they can influence the physical and chemical structure of the soil itself, as well as the microorganisms that live in it^[159]. For instance, in addition to

disseminating pollutants in the surrounding environment, MPs can modify the density and cohesion of the soil sediment particles, influencing interstitial water flow and root penetration. Fundamental symbiotic relations between plants and microorganisms can also be impacted by MP bioavailability. Both positive^[160-162] and mainly negative^[163,164] impacts of MPs on plant development have been reported.

Eriksen *et al.*^[165] reported that about 268,940 tons of plastic float at the surface of the sea; however, this figure will undoubtedly have increased, not least as a result of the COVID epidemic and a resulting rise in the use of personal protective equipment^[166]. The accumulation of plastic in the surface layers of marine water, a compartment originally rich in organic matter resulting from microbial activity, further stimulates the abundance of microorganisms, in addition to making complex organic compounds bioavailable in the atmospheric/aquatic transition zone. This can result in decreasing penetration of solar rays to deeper layers, impacting primary productivity and resulting oxygen production, in addition to modifying the dynamics of gas exchange between atmospheric and marine compartments^[167].

Dissolved organic carbon (DOC) is a significant component in the carbon cycle and is recognized as the main reduced carbon reservoir on Earth^[168]. Several bacterial groups are able to transform MPs into dissolved carbon sources, which could be the source of the high levels of dissolved organic carbon recorded in ecosystems with significant MP concentrations^[169].

The concentration of DOC released by plastic degradation increases in surface waters^[170], potentially stimulating heterotrophic bacterial activity and the rework of Dissolved Organic Matter (DOM). This results in increases in bacterial respiration and oxygen consumption, directly affecting the biogeochemical balance of this stage of the carbon cycle. Additionally, “transitioning” or production of by-products of plastic degradation, available as electron donors, potentially stimulates the concentration of microbe-plastic aggregates, which are recognized to influence DOC cycling in the ocean^[129]. MPs may influence the growth of carbon-cycling microorganisms in the ocean^[171,172].

Still, the impact of MPs on the carbon balance in the marine environment is not limited to microscopic aspects. Recent research suggested the MPs assimilation by zooplankton as a booster of water deoxygenation, since, according to Kvale *et al.*^[173], the fecal pellets resulting from this process potentially present lower density, promoting greater buoyancy of the eliminated fecal particle and reducing the marine snow flux. Thus, the higher concentrations of carbon in the surface strata water column, as particulate organic carbon, would reduce the ocean’s capacity to absorb carbon from the atmosphere^[174-176].

Therefore, based on the above-cited data, it is reasonable to consider that the omnipresence of MPs on the Earth, especially in aquatic environments, will affect carbon cycling and the global productivity of the oceans. In addition, the complexity of the biogeochemical carbon cycle makes the projection of impacts in the various compartments of this cycle on the Earth difficult. More studies are needed for a global prediction of the effects of MPs on this specific biogeochemical cycle.

Nitrogen

This vital nutrient plays a fundamental role in energy and cell production, assuming several chemical forms during microbial metabolism. For instance, denitrification is of significant importance in controlling the levels of reactive nitrogen in coastal environments. Denitrification takes place in the lower oxygen levels where nitrate (NO_3^-) and nitrite (NO_2^-) function as the terminal electron acceptor in the oxidation of OM (Queiroz *et al.*^[177]). Through denitrification, N is removed by converting NO_3^- and NO_2^- to gaseous N compounds. Nitrification can also take place in surface waters, transforming ammonium (NH_4^+) to NO_2^- .

and finally to NO_3^- . Usually, nitrification and denitrification reactions are critical for the balance of excess N in contaminated areas, as well as controlling productivity in N-limited environments^[178]. However, the impact of MPs on the recycling of inorganic N has been scarcely addressed. Based on laboratory assays, Cluzard *et al.*^[179] and Seeley *et al.*^[180] suggested that PE bioavailability to microbiota raises ammonium levels and impacts N cycling, perhaps stimulating the eutrophication process. Both these studies affirmed that nitrogen biogeochemical processes in subaquatic sediments can be significantly impacted by various polymeric compounds that can act as organic carbon substrates for microbial strains. Notably, polyurethane foam (PUF) or polylactic acid (PLA) is able to stimulate nitrification and denitrification processes^[180]. Additionally, the same authors recorded that the presence of PE significantly negatively affected the abundance and structure of the microbial communities, finally impacting the nitrification/denitrification balance. Li *et al.*^[181] evaluated the influence of five types of MPs on activated sludge. MP presence resulted in a significant neutralization of the nitrification reactions. Based on such studies, the availability of MPs in the environment can be stated to disturb ecological structure, leading to a potential imbalance of biogeochemical processes linked to nitrogen cycling.

Phosphorus

There is still a lack of information on phosphorus geochemical cycling and potential MP impacts on phosphorus transformations in the environment. However, according to the scarce data available, MPs can disturb the biogeochemical balance by modifying the structure of microbial groups in the sediment and impacting enzymes and genes involved in phosphorus metabolism, which, in turn, would affect phosphorus nutrient cycling^[182]. Liu *et al.*^[121], in a laboratory assay, showed that the addition of MPs resulted in an increase in total and soluble P levels. However, additional phosphorus cycling assays are still necessary to define more clearly the impact of MPs on terrestrial and aquatic environments.

Calcium

Microorganisms, mainly cyanobacteria and heterotrophic bacteria, are responsible for the transformation of calcium salts in the cycling of rocks and stones^[5]. Indeed, it is probable that phototrophic microorganisms were responsible for the formation of the first soils containing organic carbon through the degradation of silicate rocks^[183]. Endolithic cyanobacteria have been demonstrated, using SEM plus EDX, to redeposit previously solubilized gypsum around their cells within the rock^[184], demonstrating a very short calcium cycle. There is also considerable literature on biomineralizing and calcifying bacteria (mainly heterotrophs) that dissolve calcium substrates^[185,186] and that produce calcium carbonate crystals^[187-190]. Although it has been determined that the level of Ca in seawater has decreased over time and that this is due to decreased carbonate weathering with increased sedimentation^[191] there is no information on the interaction between microorganisms involved in the calcium geochemical cycle and MPs.

However, in a similar way to carbon, the calcium biogeochemical cycle does not occur only at the microbiological level, however. Biomineralization, for instance, the process responsible for the formation of the mollusk shell, represents a fundamental physiological mechanism for the survival of these animals. It consists of the use of dissolved ions to produce solid minerals^[192], involving several biomolecules, especially proteins^[193]. The resulting products of biomineralization include teeth and bones, the exoskeleton of coral, mollusk shells, and the skeletons of many other organisms. Biominerals are widely distributed in the environment, presenting several fundamental ecological functions. Until now, at least around 60 varied biominerals have been recorded, playing a varied range of roles, including tissue composition, embryonic and UV sheltering, predation protection, nutrition, reproduction, light or magnetic field resistance and mineral ions^[194-196]. Calcium carbonate is the most abundant biomineral in the metazoan group skeleton^[194,195,197,198].

Biomineralization is also extremely important for the formation of the mollusk shell. It has been suggested that, as feed filters, marine mollusks, especially bivalves, are impacted by MP exposure^[14]. MPs have been recorded in several common commercial species such as mussels, scallops, oysters, and clams^[199]. The negative influence of MPs on these organisms is varied^[200]; the majority of published papers deal with bioavailability, absorption pathways, transference and transformation paths, and toxicological impacts^[201]. Han *et al.*^[202] indicated that MPs impact the biomineralization process by changing the appearance of biominerals and the expression of biomineralization-related genes. MPs may be incorporated into the shell structure, highlighting a new pathway by which MPs may accumulate in bivalves^[203]. MPs can affect the production of calcite and aragonite crystals, which are key components in shell production^[202,204-206]. Much remains to be studied regarding the impacts of MPs on biogeochemical cycles.

CONCLUSIONS AND FUTURES PERSPECTIVES

Throughout their evolution, humans have created a series of new chemicals with the aim of facilitating their survival on planet Earth. Only recently has the overpopulation of the planet begun to show that the old ways cannot continue. The development of sustainability-based plastic management concepts and measures is long overdue. This chronological lag has produced the critical challenge of creating and improving techniques to answer the problems of contamination of natural environments. In the case of microplastics, this is a challenging issue. The peculiar chemical composition and consequent toxicity of MPs not only protect them from the planet's purification mechanisms, but also make them effective carriers of a diverse range of pollutants. This facility becomes even more intense during the degradation of the plastic matrix, not only intensifying its ability to attract chemical pollutants, but also increasing its qualitative versatility in terms of attracting new compounds from the contaminated environment.

One of the most critical issues regarding the impact of microplastics in natural environments is their potential toxicity and direct impact on living organisms. Their influence on the cycling of elements, through the micro or macro level, in natural systems and exchanges between the different geochemical compartments affect the pre-established balance of the entire planet. It is not wrong to suggest that microplastic combines the negative effects of domestic sewage (an imbalance through the enrichment of nutrients, resulting in the eutrophication of aquatic ecosystems) and the toxicity of industrial waste (that directly affects the trophic chain).

So, the development of methods to manage and alleviate the problems of MPs in the environment is a race against time; these particles are already ubiquitous on the planet and are closely linked with the potential for the spread of other contaminants.

In this article, the abilities of plastic microparticles to take up and transport chemical pollutants are correlated with their basic properties, which can change when the particles are exposed to various environmental compartments. The similarities between the well-known biogeochemical cycles of the Earth and the recycling of microplastics are described. The simple characteristics of industrially produced plastics are described as a basis for encouraging the development and application of sustainable methods in the management of plastic manufacturing and for reducing the impact of microplastic pollution on the environment. The pollutant-carrying capacity of microplastics is dependent on the interaction between the plastic matrix and the environmental conditions; the evolution of microplastic management should therefore focus on creating more inert plastic matrices and less toxic inputs. This could result in their safe recycling in the environment, both chemically and biologically.

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Authors' contributions

Conception; development of the theory; discussion of results and contribution to the final manuscript: de Almeida MP

Conception; development of the theory; discussion of results and contribution to the final manuscript: Gaylarde CC, da Fonseca EM

Discussion of results and contribution to the final manuscript: Baptista Neto JA, Delgado JdF, Lima LdS, Neves CV, Pompermayer LLdO, Vieira K

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Conflicts of interest

All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

All authors give our consent for the publication of this article.

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