A micro(nano)plastic boomerang tale: A never ending story?

M. Oliveira [a, *], M. Almeida [a], I. Miguel [b]

[a] Department of Biology & CESAM e Centre for Environmental and Marine Studies, University of Aveiro, Campus Universitário de Santiago, Aveiro, 3810-193, Portugal
[b] Portucalense Institute of Human Development & Department of Psychology and Education, Portucalense University, Porto, 4200-072, Portugal

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abstract

Plastics are an integral but largely inconspicuous part of human daily routines. Associated with a high production and single use nature of several products, small plastic particles became ubiquitous. Due to processes like water currents and winds, plastics may occur far from their place of origin and affect biota at different environmental compartments. In the environment plastics can degrade into increasingly smaller particles, reaching a nanometer size which increases their potential to be incorporated by organisms. Currently it is recognized that the plastics in the environment are reaching humans via contaminated food, drinks, and air but their effects on humans are largely unknown. In this paper, the potential exposure routes and effects to humans are discussed and approaches to decrease impact of microplastics to humans presented.

1. Introduction

Since the 18th century, human activities have been associated with the production and release, to the environment, of large amounts of chemical compounds and residues. Up to World War II, it was assumed that the release of unwanted gases to the atmosphere and masses of liquids to water courses, would not have consequences as they would be carried away from pollution sour- ces and diluted. However, by the end of 1950's, this dilution model was invalidated as numerous silent catastrophes like the Minamata and Itai Itai diseases proved that pollutants released into the environment can return and affect humans. Currently, despite these historical evidences, human activities continue to release large amounts of materials into the environment (intentionally or accidently) that may have unknown long-term consequences to the environment and ultimately to human health. Among those materials are engineered nanoparticles and plastic products. If the use of engineered nanoparticles by humans is a recent technological development, plastics are being used for more than 80 years, at increasing rates.

The presence of plastics in the environment is a global environmental issue and a result of modernization. Unlike many other environmental contaminants, the majority of the small plastic particles found in the environment are produced as an unintended side effect of routine daily human activities. They are widespread, and their potential effects may occur everywhere in the environment, away from their origin source. Thus, the potential risks of plastic debris for environmental and human health is the subject of an increasing interest among scientists, policy makers and general public [1]. Despite the general recognition that small plastic particles can be found in different environmental compartments (freshwater, seawater, sediments, soils and air), the current under- standing of the consequences of these particles at levels found in the environment can still be considered scarce. The complex nature of these particles that may contain, as a results of their synthesis, different polymeric chains, residual monomers, chemical catalyzing agents, additives and non-intentionally added substances carried over from the raw materials [2], allied with the wide range of possible sizes, shapes, and surface functionalizations, make the study of their real impact a challenge. Furthermore, once released into the environment, due to their increased surface area:volume ratio, and surface hydrophobicity, they may adsorb and concentrate other contaminants (e.g. polycyclic aromatic hydrocarbons, polychlorinated biphenyl, pesticides, metals) [3,4] and may serve as carriers for microorganisms that attach to their surface [5,6].

Once in the environment, plastic particles may be subject to a variety of abiotic and biotic processes that lead to their degradation and fragmentation into increasingly smaller sizes, potentially altering their biological effects. An immediate question that arises is "Are there direct consequences to humans?" In this critical review potential exposure routes and effects to humans are discussed, and research/actions needed to prevent pernicious effects proposed.

1.1. *Plastics in the environment: sources and environmental impact*

The term plastic is generally used to describe plastic polymers, to which additives are added to provide wanted properties to the final product [7]. Synthesized from monomers, polymerized to form macromolecular chains, plastics may have additional chemicals added during the manufacturing processes (initiators, catalysts and solvents). Additives, that can alter the nature of plastic include stabilizers, plasticizers, flame retardants, pigments and fillers. Plastics are inexpensive, lightweight, strong, durable, corrosion-resistant materials, with high thermal and electrical insulation properties [8]. They have a wide range of applications. In 2016, of the 60 million tons produced in Europe, a considerable amount of plastic produc- tion was directed towards single use applications (approximately 39.9% was used for packaging). Despite the extensive applications (e.g. construction, automobile industry, electronic equipment, medical), new applications may be expected in the future.

Currently plastics play a determinant role in modern society and humans are in contact with these materials from the moment they wake up to their sleep. Sources, fate and effects of microplastics are the subject of a high number of studies that already led to reviews in terms of properties (e.g. Ref. [9]), sources, fate and occurrence (e.g. Refs. [10,11]), analytical methods (e.g. Refs. [3,10]), effects on organisms (e.g. Refs. [10,11]), research gaps [4] and effects on humans (e.g. Refs. [2,12]).

Plastics may reach the environment at different sizes, as a result of a wide range of applications. Macroplastics released into the environment start to slowly degrade into smaller particles (micro and nano). However, micro and nanosized plastics are nowadays used in products like cosmetics, drilling fluids, and air-blasting media paints, vectors in biomedicine and have, as a recognized end use, their release into sewage systems [10]. The main sources of plastics entering the ocean are land-based activities associated with human movement and behavior (littering, inadequate industrial disposal of products, or loss during production or transport), inadequate waste management (e.g. open dumping grounds and ineffective wastewater treatment plants), recreational activities in coastal areas (e.g. food and drink packages), environmental conditions (e.g. storm and sewer overflows), run off or air dispersion of soils treated with sewage sludge (frequently used as soil fertilizer), product wear (e.g. clothes releasing synthetic fibers) [13,14] (Fig. 1). Due to their low degradation rate, plastics of varying sizes accumulate both in terrestrial and aquatic ecosystems with the marine system, being considered as the ultimate recipient. Based on estimations, between 0.8 and 2.5 million tons of microplastics are ending up in oceans [15]; 44,000e300,000 (European) and 63,000e430,000 tons (North American) of microplastics yearly applied to agroecosystems [16]; and 5 trillion plastic particles are floating in the ocean, with a total weight of 270 million tons [17]. The quantification of environmental levels of small plastic particles of sizes bellow 300 mm present in the marine environment is a methodological challenge as the pore of nets is easily clogged up and biota may also be compromised. Micro(nano)plastics from contaminated soils or waters may become airborne and dispersed, decaying and contaminating different compartments. Even particles in the sea surface may, by wave action form sea spray, generate aerosols up to a few micrometers [18].

Plastic pollution constitutes an additional stressor to the ocean ecosystem already under anthropogenic induced pressure (e.g. acidification, global warming, overfishing, and chemical pollution of substances like metals and persistent organic pollutants) [15]. In addition to the effects of the particles themselves, there is also the concern that they may constitute a potential source of chemical additives, hazardous unreacted and dangerous residual monomers that may be carcinogenic and/or mutagenic [19], as well as environmental contaminants like polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), metals, pesticides and pharmaceuticals. As a result of its low molecular weight and lack of chemical binding to the plastic structure, additives are susceptible to leaching along a concentration gradient [12]. Fragmentation of microplastics will expose new surfaces facilitating the migration of additives [12].

Effects on marine life and ecosystems may occur in different ways. Plastic particles of sizes higher than 5 mm (macroplastics) have been reported to cause entanglement (e.g. abandoned fishing gear), that may compromise animal movement, growth and be fatal; physical damage or blockage of the intestinal tract may lead to infection, starvation and potentially death. For micro(nano) plastics (sizes bellow 5 mm), there is an intense research to study their effects as they are available for ingestion to a wider range of

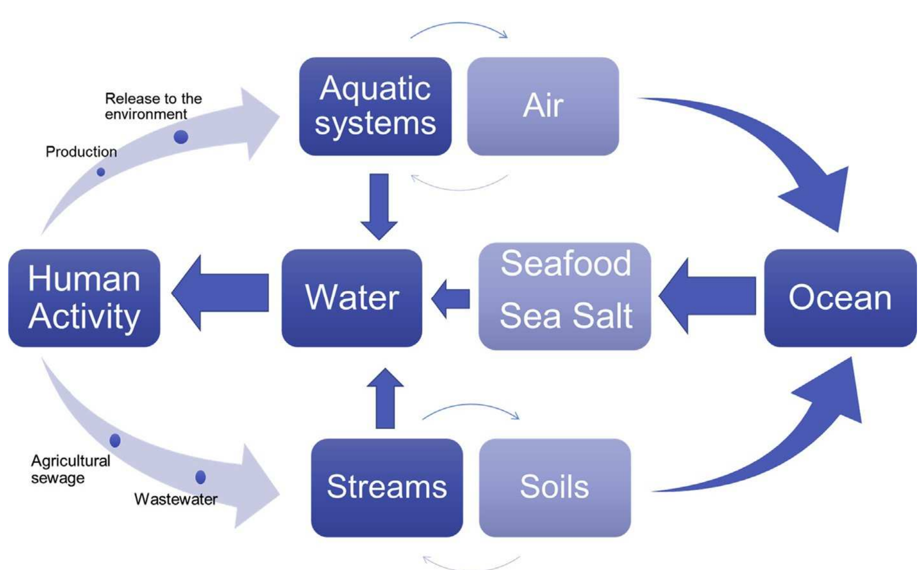

Fig. 1. Schematic representation of micro(nano)plastics circulation in the environment.

organisms than macroplastics, including organisms at the base of the food web (e.g. phyto and zooplankton). They have been able to induce decreases in zooplankton feeding rates and reproduction [20], concentrate environmental pollutants [21], modify the distribution, biotransformation and effects of other environmental contaminants (e.g. PAHs and pharmaceuticals) upon simultaneous exposure [22,23]. They have been reported to induce genotoxicity and neurotoxicity in fish and mussels [22,23], promote alterations of behavior [24] and cause endocrine disruption [25] in fish. Laboratory studies suggest that microplastic particles may be passed up the food web [26] and thus, also potentially be a vector for the transfer of environmental contaminants. This trophic transfer may eventually reach humans. Small plastic particles may also act as a dispersion vehicle for invasive species and pathogenic organisms. The slow dispersion speed of plastics may allow species to adapt to changing environmental conditions and have detrimental effects on marine species diversity [5].

1.2. *Plastics and human health: potential sources and effects on human health*

The assessment of the real risks of micro(nano)plastics to human health, requires understanding environmental levels and pathways of exposure [12,27], calling for new approaches and improvement of analytical methodologies. One of the main chal- lenges is the isolation of small plastic particles from the environ- mental matrices. For water samples, new approaches are needed to efficiently isolate particles of sizes below 300 mm, in representative volumes, without compromising biota nor sampling efficiency. The commonly used approaches to identify micro(nano)plastic parti- cles rely on visual examination of the particles to separate micro-plastics from other materials. In biological matrices, procedures usually involve extraction and degradation of biogenic matter, which may compromise the integrity of polymers. Thus, the opti- mization of cost effective, efficient and fast procedures is highly needed. Microscopy based technologies like Raman and super resolution, are available to help identify different types of micro- plastics. Together with Nile Red and different Raman based protocols (CARS and SRS), they represent the latest identification techniques [14]. However, these techniques are time consuming and the size of particles that may be identified is limited by reso-lution limits to sizes in the range of mm.

It is recognized that small plastic materials present in the environment may have the potential to contribute directly or indirectly to human health risks, although so far no deleterious effects have been reported in humans. Micro(nano)plastics present in the environment may reach humans through the digestive tract (via food [28] products like bivalves (clams, mussels oysters [29,30]), fish [31], canned food, table salt [32] and drink products like water and other contaminated beverages [33,34]), via inhalation of airborne particles [35] and, in the case of nanoplastics, via dermal exposure [2]. Species like mussels, that are consumed as a whole, enabling the ingestion of micro(nano)plastic particles present in their gastrointestinal tract, were considered of major concern whereas a lower relevance was given to fish as microplastic particles have been reported within the gastrointestinal tract, usually not eaten by humans. This notion of potential risk must however be reconsidered as the presence of microplastics in the skin and muscle of several pelagic and demersal fish species of commercial interest, as well as muscle of a prawn species [36], has been detected. Furthermore, some fish are also consumed as a whole, in their juvenile stages, increasing the likelihood of human microplastic consumption. Humans may also be exposed to micro(nano)plastics through non-environmental sources like via biomedical treatments and prosthetics [37].

The data concerning micro(nano)plastics distribution in the environment together with laboratorial approaches, have demonstrated several deleterious effects in the marine biota, that can suggest potential effects to humans (Table SI 1) [2]. However, this subject is understudied [2,12] and available data is scarce. The reported toxic effects of micro(nano)plastics in aquatic species such as immunomodulation and apoptosis [38], generation of reactive oxygen species and peroxidative damage [23], impaired neurotransmission [22], translocation of micro(nano)plastics from the digestive track to the circulatory system and internal organs [36], brain and liver and continuous inflammatory activation suggest that these particles may also be toxic to humans (Table SI 1). However, no studies are available in terms of effects of micro(nano)plastics of environmental origin on humans. Some studies are available with these materials but performed due to the use of plastics in prosthetics (Tables SI 2). These materials have also been reported to fragment, forming particles of micro and nanosize [39], able to translocate to lymph nodes and, in some cases, liver and spleen. Several reports of prosthesis failure are due to wear debris-induced osteolysis. Debris are responsible for triggering inflammatory processes that may lead to implant failure [37]. Occupational studies have also provided data on the ability of plastic fibers to penetrate in the lung tissue [40,41], and induce localized biological responses, upon uptake and persistence. Reported symptoms of fibers exposure include respiratory irritation [42], reduced lung capacity [43] and inflammation [42], potentially leading to excessive formation of reactive oxygen species and DNA damage, fibrosis and in some cases cancer [42].

One of the risks to human health frequently associated with microplastics exposure is the release of additives from plastics synthesis. However, considering the estimated low rates of exposure to microplastics (11000 microplastic particles annually [29]), based on the levels of microplastics found in bivalves and the estimated human consumption, this pathway of exposure has been proposed as of limited importance compared to other exposure pathways [2] like water and food. Experiments involving leachates from everyday plastic objects and marine litter revealed their ability to negatively affect marine wildlife, impairing larvae development (Table SI 1). These effects were correlated with release of chemicals associated with plastic production (e.g. non- ylphenol). Similar calculations and conclusions were obtained for PAHs and PCBs [44]. Combined exposures of microplastics and contaminants may lead to higher degrees of accumulation in tis- sues, decreased detoxification capacity and cumulative effects (Table S1). Thus, data suggest that although microplastics may be an additional source of human chemical exposure, food contami- nated by packaging constitutes a main source of exposure. A similar conclusion was also obtained for salt based on the small particle sizes and low prevalence [9]. However, data refer to particles larger than 149 mm. For smaller particles numbers may be considerably higher.

The contribution of micro(nano)plastics to the body burdens of contaminants depends on the concentration gradient of the contaminant in question, if higher in the plastic than the surrounding environment (e.g. cell), then the contaminant is expected to desorb.

Micro(nano)plastics may be rapidly colonized by microorganisms including harmful human pathogens (e.g. Vibrio spp), and disease carrying mosquitos [45], which may have pernicious effects on human health. Biofilms on microplastics have been reported different from the ambient environment (Table SI 1) [6]. Thus, if ingested, microplastics may promote a shift in the structure of microorganisms present, for example, in the digestive tract and compromise immunity and nutrition.

Particle size is one of the most important factors in determining the extent and pathway of uptake and clearance (although other characteristics of the particles like shape, solubility, and surface chemistry as well as the site of contact and nature of particle interaction with biological structures [12,46] play also important roles). In this perspective, nanoplastics are potentially more hazardous than microplastics because they may permeate biological membranes through endocytosis, phagocytosis and potentially through the tight junctions of the epithelium [47]. However, corona formation (in the environment and during transit in the organisms) and surface may determine their distribution and toxicity.

Despite the apparent limited human exposure to microplastics through food, long term effects must be considered. The development of analytical methods to determine plastic particles of smaller sizes may reveal a higher exposure level. Furthermore, increased amounts of particles in the environment, use of plastic products in the food chain (e.g. plastic pipes for automatic feeding of fish in aquacultures), synthetic clothes, and cosmetics suggest increased exposed levels if no action is taken.

1.3. *Social and economic impacts and potential solutions*

Something is now clear concerning micro(nano)plastics, human routines must change. In addition to ecological impacts, the presence of micro(nano)plastics in coastal areas may also have considerable social and economic impacts. Tourism may be seriously compromised in recreational areas used for swimming and water sports, not only due of aesthetic aspects but also to public awareness to the potential danger to health that the presence of micro(nano)plastics may provide (e.g. presence of pathogenic organisms, high concentrations of dangerous environmental contaminants). Additionally, restaurants, fishermen, aquacultures may also suffer economically, if local seafood is contaminated with microplastics, yielding reduced consumption and revenue. An attempt to minimize impacts like removal of plastic debris from beaches and waters has also costs for local and national authorities and environmental organizations.

There is no consensus on how to solve the problem of the particles that are already in the environment (i.e. removing them and making them unavailable to biota). Nonetheless, actions must be taken to minimize micro(nano)plastics formation and environmental release considering that simply stop using plastics does not appear a feasible solution. Steps may be taken at different levels, from production (e.g. conditioning of products, usage of less pernicious additives, improving products design) and consumer usage and selection (e.g. choice of material e single use *vs* reusable, selection of products with constitution described and less toxic) and increased recycling rates. Improving waste disposal, handling and waste infrastructure (e.g. drains) are also important measures. Reusing, recycling and repurposing plastics at the end of their useful life can decrease the problem of plastic debris. This may be achieved through economic stimuli like tax benefits in the reuse of plastics as raw materials for industries and in consumers deposit-refund scheme for drink containers and packaging.

Education may be one of the most important approaches to help solve pollution problems associated with human daily routines. To counter the global environmental challenges and achieve sustainable individual behavior, interdisciplinary efforts have to be made to understand the key factors and processes behind behavior causing these challenges, predicting their development over time, and eventually changing the system enough to mitigate negative outcomes [48]. Environmental education in formal contexts has been pointed as having a crucial contribution, in collaboration with communities, for the development of sustainable lifestyles that can result in meaningful socioecological outcomes [49]. In this approach, that should begin in preschool period, teaching programs written for environmental education, should increase awareness of the students towards nature, environment and the importance and consequences of individual actions. Democratic environment should be formed by supporting activation of the students and their solutions about the environmental problems. Various civilian establishments, associations, clubs and unions should arrange activities to increase the awareness of the public towards the environment. By providing an active involvement of the individuals and taking attention of the public opinion, some applicable activities and competitions should be arranged. Using mass communicative instruments (internet and media), environmental education should be established in society aiming at reducing consumption and preventing littering behavior. The public must be well informed about known risks and available alternatives. Benefits of this global action are multiple. For example, communities that thoroughly adopt green philosophies and practices will not only lessen their contributions to escalating environmental problems but increase their resilience to the forthcoming challenges of environmental risks. Also, higher levels of social welfare and stronger support from citizens, community groups and organiza- tional entities can be achieved as a result of appropriately designed environmental policies [50].

The use of alternatives to plastics like glass material especially for storing food and microwave; use of reusable water bottles made of biodegradable materials; use of reusable bags made of alterna- tive materials like cloth can also be strategies to be adopted.

Legislative framework that may aid in plastic ocean pollution challenges has been made in the last decade. Marine debris due to plastics is one of the descriptors for Good Environmental Status in the Marine Strategy Framework Directive (2008/56/EC); The Waste Framework Directive (2008/98/EC) introduced a "polluter pays" principle and the notion that handling of plastics should follow the four Rs (Reduce, Recycle, Re-process, Recover); the European Directive on packaging and packaging waste (94/62/EC) established the framework for sound management of packaging and packaging waste and was amended by Directive (EU) 2015/720, that focused on reducing the consumption of lightweight plastic carrier bags in the EU and introduction of plastic bag tax by the end of 2018. The International Convention for the Prevention of Pollution from Ships (MARPOL 73/78) aimed to reducing illegal dumping; the Port Waste Reception Facilities Regulations 2003 (to deliver EU DIREC- TIVE 2000/59/EC targets) consolidated plans for responsible ship-generated waste and cargo residues management ensuring adequate port reception facilities are available to meet the needs of users. The latest alteration is the preparation of the Directive (EU) 2018/0172, regarding the ban on single-use plastics that will regulate the production/usage of certain types of plastic and enforce measures to the state members to reduce the amount of plastic waste in the oceans.

The life cycle of micro(nano)plastics is long, regardless of their source (primary *vs* secondary). It is possible to verify that the majority of the man-made products that are present in our daily lives will, most definitely, find its way into the soil and water reserves. But unlike degradable substances that will suffer decomposition and re-enter the base-chain as nutrients, microplastics are not degraded, just weathered into smaller and smaller particles, until it is almost impossible to verify its existence. Nonetheless, they are likely to continue exerting its effects in the biota. For plastics, size matters. The smaller the particle, the easier it is to be ingested/ incorporated by a wider range of organisms and enter the cells. At the same time, it may be more difficult for the organisms to excrete them. Thus, they may remain as foreign bodies leading to consistent and continued inflammatory processes that may affect cellular viability and ultimately lead to apoptotic and necrotic mechanisms. Another consequence to the inability of excreting microplastics is the accumulation in the food chain, that might find its way into humans. Our boomerang route can be described as throwing macro/micro/nanoplastics and catching several nanoplastics from different routes. Can this route be stopped?

2. Concluding remarks

The degradation of the environment that we are experiencing today is expected to increase considerably over the next few decades, due to populational increase and industrial activities. The presence of micro(nano)plastics is hypothesized as a long-lasting problem for which a solution is not yet discernible. The available data show that the plastic particles that have been thrown in the environment (as large particles or in a micro(nano)size) are nowadays returning in different sizes and means to humans. They are present in human food sources, drinks, air household, in sizes that are potentially dangerous and in conditions that may allow leaching of additives, some toxic at low concentrations. Despite the lack of direct evidences of the consequences to humans of these environmental particles, data on biota suggest their pernicious effects (direct, via simultaneous exposure or via adsorbed contaminants). The consequences of micro(nano)plastics are also economical, particularly for countries with an economy based on sea activities like tourism, fishing and aquaculture, as their pres- ence compromises the value of those products. These are recog- nized measurable effects. If in some countries the use of some plastic products is already under control (e.g. microbeads in cosmetics, taxation of plastic bags), humans are betting on nano- technology and the use of nanoplastics (e.g. paints, cosmetics) that are thrown in the environment as a result of their end use. These particles are more difficult to detect in the environment but potentially more dangerous as the low size of nanoparticles provide them with specific characteristics and reactivity, dependent on their size. They are more bioavailable and able to be incorporated by cells by different methodologies.

The removal of micro(nano)plastics from the environment is an enormous challenge and requires different approaches to modify daily routines that contribute to the use and release of plastic particles in the environment. This can be achieved through public education and economy stimulus that reward environmentally friendly actions and taxation of actions leading to plastic debris formations. Research on alternative material and conscious use of plastic may stop a boomerang release-effect plastic associated story.

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Appendix A. Supplementary data

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