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Micro- and nanoplastics current status: legislation, gaps, limitations and socio-economic prospects for future

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The pollution caused by micro- (MP) and nanoplastics (NP) in the planet's ecosystems has gained significant interest in recent years due to their environmental impact and effects on the health of living organisms. Given this, it is necessary to conduct a comprehensive analysis of the actions required to mitigate their impacts. This paper analyzes existing legislation across different countries and regions, including Europe, North America, China, Russia, India, Brazil, Mexico, and the global initiatives undertaken by the United Nations. Furthermore, it highlights the need for additional measures to mitigate the impact of MP/NP in future years, such as the development of technologies for the separation or degradation of these particles in water intended for human consumption and in wastewater treatment plant effluents, studying plastic particulate material in the air considering meteorological parameters, MP/NP detection protocols in human fluid samples, creating truly biodegradable polymers for use as bioplastics, and establishing institutions responsible for the management of plastic waste. The study also shows the current state of abundance (characterization and quantification) of MP/NP in different environmental matrices based on reports from recent years, and identifies key research opportunities and actions required to evaluate the risks and toxicity associated with MP/NP. Socio-economic aspects are considered, including the impact of MP/NP on different regions, by associating economic and human wellness parameters to plastic waste generation by using available data from 148 countries. As result of this analysis, both the most populated and developed countries contribute to MP/NP generation, however, they have different capacities to address this problem due to social circumstances. The solution to this problem requires efforts from authorities, industry, the scientific community, and the active participation of the population, then, resolving social, political, and economic issues between countries and regions of the world is necessary.

KEYWORDS

microplastics, nanoplastics, mismanaged plastics, legislation, gaps, study opportunities, public awareness, socio-economic aspects

Introduction

Plastics were invented in 1860 from organic polymers derived from fossil hydrocarbons. However, their demand and manufacturing began to increase since 1940, replacing common materials up to that time, such as wood, metals, ceramics, leather, glass, paper, and vegetable fibers, among others (Khairul Anuar et al., 2022). Today, plastics have become a feedstock in all industries, from textiles and automotive to food, due to their physical and chemical properties, such as low weight, heat resistance, translucency or transparency, malleability, and hardness (Maurya et al., 2020).

The global manufacture of plastics has been increasing year after year. It has been estimated that in 1950, 1.7 million tons (MT) were produced, while in 2018, its production reached 359 MT, with 17% of the total attributed to Europe, 18% to North America, and 51% to Asia (Worm et al., 2017; Plastics Europe, 2019). Currently, 40% of the world's plastics production corresponds to the packaging industry, 20% to articles of common use, 20% to construction, and the remaining 20% to the agricultural, electrical, and automotive sectors (Oliveira et al., 2020). By 2017, it has been estimated that over 8000 MT of plastic had been manufactured cumulatively worldwide, with 2500 MT currently in use. It has also been calculated that up to 2015, 6300 MT of plastic waste were generated, with 800 MT being incinerated, 600 MT being recycled, and approximately 4900 MT being disposed of and accumulated in landfills or natural environments (Geyer et al., 2017). In 2019, 31 transnational companies reported the amount of plastic generated as a result of their commercial activities. Coca-Cola reported an annual world production of 88,000 million (M) single-use plastic bottles, equivalent to 3 MT per year, followed by Nestle with 1.7 MT and Danone with 0.73 MT (Schächtele, 2020). Therefore, in addition to the large amount of plastic waste generated by the population, it is evident that the industry also contributes significantly.

Undoubtedly, plastics have improved the quality of life of the population, bringing with them facilities and comforts in daily and work activities, including devices and equipment that improve human health and extend longevity. However, their high production and inadequate disposal have made them the focus of attention in recent years due to being a source of micro- and nanoplastics (MP/NP) and having negative impacts on ecosystems and health. In this mini-review, the dispersion of MP/NP through different ecosystems, MP/NP quantification in different matrices, current international legislation, synergism of MP/NP with other emerging pollutants, gaps, study opportunities, and future actions are analyzed. Additionally, social, and economic aspects from 148 countries are evaluated to determine the correlation between the economy or productivity, human wellness, and the generation of plastic waste that leads to the formation of MP/NP. All these perspectives aim to contribute to solving the impact of MP/NP in future years.

Materials and methods

To develop this work, more than 160 different sources were analyzed: Papers published recently and from a few years ago, some specialized books and book chapters, databases of non-governmental organizations such as the WHO, World Bank, World Economic Forum, OECD and UN platforms, international press reports, as well as government and official internet sites from several countries. The articles consulted were found in different databases using keywords such as microplastics, nanoplastics, plastics, mismanaged plastics, legislation, pollution, airborne, soil, water, health, toxicological effects, environment, formation, applications. On the other hand, legislation on plastics and microplastics was analyzed by accessing directly on government official sites of the most economically important countries; so that all this information allowed us to conclude on the studies and actions required to solve the problem from social, economic, scientific and health perspectives.

Origin and formation of micro- and nanoplastics

Although resistance to heat and lightness makes plastics materials with great advantages in the manufacture of useful products, these properties make plastics a problem when they become waste in the environment since their biodegradation is technically impossible under normal conditions in nature (Khairul Anuar et al., 2022). As a result of their widespread use, plastics can remain as waste easily visible to the human eye (macroplastics). However, in addition to the negative impact that these macroplastics cause in ecosystems, there is another potential issue derived from these materials: invisible plastic particles that are also difficult to break down and are classified as emerging pollutants. These plastic particles can be classified based on their size, chemical nature, and the way in which they are produced or released into the environment.

There is no official international agreement for their size classification; however, considering at least one of their dimensions, plastic particles can be classified as microplastics (MP) with a size between 1 μm and 5 mm, and nanoplastics (NP), with a size smaller than 100 or 1000 nm (Yang et al., 2021; Schröter and Ventura, 2022). The chemical nature of plastic particles and materials depends on the monomers from which they are formed: monomers linked in a linear or branched fashion (methyl, phenyl, fluorinated, or chlorinated groups) linked through nonpolar C-C or C-O covalent bonds. Examples of these are polyethylene (PE), polypropylene (PP), polystyrene (PS), polytetrafluoroethylene (PTFE), polyvinyl chloride (PVC), and polyethylene terephthalate (PET). Therefore, MP/NP represent a challenge in characterization and detection because they have different chemical structures, shapes, and physical properties.

Considering the way they are produced, these particles can be primary or secondary. Primary MP/NP are manufactured in small sizes, generally intended for medical applications (such as sensors, implant coatings, drug delivery), and personal care products (added to soaps, cosmetics, toothpastes, scrubs). On the other hand, secondary MP/NP are produced as a result of friction, abrasion, degradation, fragmentation, and/or erosion of larger particles and/or large pieces of plastic (Andrady, 2011; Auta et al., 2017). These particles are generated from bags, wrappers, toys, containers, single-use utensils, synthetic clothing fibers, tubes, paints, household and industrial abrasive products, beauty and hygiene products, among others. However, they can also come from thermosetting materials, from the abrasion and weathering of tires, road signs, and marine coatings. It has been estimated that the concentration of secondary MP/NP in the environment is higher than the concentration of primary MP/NP (Boucher and Friot, 2017).

Secondary microplastics/nanoplastics (MP/NP) are generated from the degradation of larger plastic objects (macroplastics). Degradation can be classified as abiotic and biotic degradation (biodegradation). Abiotic degradation occurs due to environmental physical and chemical effects (temperature, UV radiation, wind, waves), while biodegradation occurs due to the effect of microorganisms or enzymes (Restrepo-Florez et al., 2014) only under controlled temperature conditions (25°C–37°C), in the presence of suitable media (saline aqueous solutions), enzymes, or microorganisms capable of degrading these polymers. The advantage of biodegradation lies in the mineralization and transformation of plastics into simple organic compounds that can be incorporated into the cycles of elements (carbon, nitrogen, sulfur); however, its disadvantage lies in the long times required (up to 6 months). In addition, microorganisms with this capacity are not found in all ecosystems (Banker et al., 2016). Abiotic degradation can be classified into thermal degradation (due to high temperatures inducing structural changes), mechanical degradation (due to the action of mechanical forces physically breaking the material, such as wind and waves), and chemical degradation (Li et al., 2004; Chen et al., 2018).

Chemical degradation can be classified as photodegradation, thermo-oxidation, and photo-oxidation. Photodegradation is the modification of plastics by solar radiation (such as discoloration, brittle surfaces, decrease in mechanical resistance). Thermo-oxidation consists of the degradation of plastics due to the action of light, heat, or chemical attacks from the reaction with oxidizing species, causing the loss of their properties. Finally, photo-oxidation consists of the generation of oxidizing radicals from UV light (Pospisil et al., 2006; Gardette et al., 2013). MP/NP are generated from the chemical degradation of plastic waste when it floats in the sea or in continental water, in sediments or in soils, and is exposed to solar radiation, facilitating the oxidative degradation of its structural polymers. The largest amount of MP/NP is generated from commonly used plastic articles and products that are irresponsibly disposed of in the environment.

Another common source of MP/NP generation is from the washing of clothes and synthetic fabrics (plastic fibers). It has been reported that during a wash cycle, fibers, microfibers, MP, and NP are detached. Yang et al. (2021) reported that 1 kg of synthetic clothing releases 2.1–3.3 × 10̂14 NP particles. It has been estimated that in 2020, the world production of synthetic textile fibers was 68 million metric tons (textile market report in the folder). Considering the world population, it is estimated that about 11 kg *per capita* of these fibers are consumed to manufacture clothing (Boucher and Friot, 2017), which may have generated up to 2.86 × 10̂28 NP *per capita* per year. The most populated countries generate more MP/NP as laundry waste. Taking 1 g of cloth as a reference, it can release 1.4 mg of NP after a wash cycle (Yang et al., 2021). Based on their respective populations, China, India, the United States, and Mexico would generate around 22, 21, 5, and 2 million metric tons of NP per year."

Dispersion of micro- and nanoplastics in the planet's ecosystems

Microplastics/nanoplastics (MP/NP) are ubiquitous and spread practically everywhere on the planet. However, the mechanisms of dispersion for these materials are not well known. This section will address the various ways in which dispersion occurs. The high production of everyday plastic items, inadequate disposal practices, and exposure to physical and chemical phenomena in natural environments (such as solar radiation, abrasion from waves and tides in the sea, high temperatures, and wind erosion), as well as in industrial and household settings (abrasion by cleaning products, washing clothes, and mechanical friction of plastic components), contribute to the generation and dispersal of MP/NP in the air, on the ground, into the soil, in the sea, in continental and subterranean water, in snow, and on mountains (Wu et al., 2020; Barnes et al., 2009).

The dispersion of the PM/NP depends to a great extent on the characteristics of these particles due to their physicochemical nature, such as their size, morphology and density. The density allows particles of different plastic polymers to float or sink in different types of water (Ziani et al., 2023), as well as their drag by airborne. While it is impossible to measure the exact amount of MP/NP present in different environments worldwide, some authors have reported specific concentrations of these substances in certain locations and environments from the sampling of air, water and soil (Table 1). For example, MP particles measuring 607 μm were found in Antarctica soil at a concentration of 13.6 particles/50 mL (Perfetti-Bolaño et al., 2022). Fibrous MP has been detected on Everest at a concentration of 30 fibers/L (Napper et al., 2020), and in forests, wetlands, sanitary landfills, and industrial zones, the average concentration is up to 106,000 particles per kg of analyzed soil (Leitao et al., 2023). The presence of MP/NP in remote areas can be attributed to the increase in tourism, expeditions, and the transport of particles through the air and sea.

City dust contains particles generated by the abrasion of tires and shoes with synthetic soles on pavement, as well as from plastic utensils, infrastructure, and artificial grass (Essel et al., 2015; Lassen et al., 2015). This dust can be transported through the air and rise at high temperatures, like the transport of dust particles with a size <2.5 μm from the Sahara Desert to the American continent (Zauli Sajani et al., 2012; Yu et al., 2015). Airborne transport occurs relatively quickly, within days to weeks, making the atmosphere the fastest route for the spread of MP/NP (Allen et al., 2022; Allen et al., 2022), particularly for NPs, which have a longer suspension time. Several studies have been conducted to evaluate the presence of MP/NP in the air in a passive and active way. An investigation in Paris revealed concentrations of 0.3–1.5 fibers/m3 of air sampled on rooftop buildings, while concentrations of 0.4–56.5 fibers/m3 were found inside these structures (Dris et al., 2017).

An important phenomenon related to the air transport of microplastics/nanoplastics (MP/NP) is atmospheric deposition, which involves the re-incorporation of these particles into the soil, water, or ecosystems. Deonie Allen and others estimated that up to 25 million metric tons (MT) of MP/NP with diameters ranging from 8–180 μm are transported annually through the marine atmosphere and deposited in the oceans (Abbasi, 2021; Allen et al., 2022). In the French Pyrenees, NPs

TABLE 1 Concentrations and type of MP/NP quantified in different environment locations and matrixes.

Matrix/environment		Location/region	Polymer	Particle size of MP/NP	Concentration	Reference
Water	Surface water and sediments	Three Gorges Dam (China)	PS, PP, PE	3–50 µm	1.6–12.6 mg/m³ (surface water) 25–300 ng/kg (sediments)	Di and Wang (2018)
	Raw and treated water	WTP (Czech Republic)	PET, PP, PE	<1 µm	1473–3605 MP/L (raw water) 338–628 MP/L (treated water)	Pivokonsky et al. (2018)
	Surface water	Wastern Lake Superior (USA)	PE, PS, PET, PP	<5 mm	37000 fibers/km²	Hendrickson et al. (2018)
	Underground and drinking water	Water supply chain (Germany)	PE, PET, PVC	50–150 µm	7 MP/m³ (underground water) 0.7 MP/m³ (drinking water)	Mintenig et al. (2019)
	Surface water	Yellow River (China)	PE, PP, PS	<200 µm	497–930 MP/m³	Han et al. (2020)
	Surface water	Goulburn River (Australia)	PET	36 µm–4.6 mm	400 MP/m³	Nan et al. (2020)
	Sediment	East Dongting Lake (China)	PET	<0.5 mm	180–693 fibers/kg	Yin et al. (2020)
	Filter residue of greywater	Farmstead (Germany)	PET	>100 µm	1.43 g/kg (Fibers of textile washing)	Müller et al. (2020)
	Clothes washing water	St. Gallen (Switzerland)	PET	<100 nm	3.3×10^{11} MP/g textile (2.1 mg/g textile)	Yang et al. (2021)
	Surface water	Jhelum River, Himalaya (India)	PE, PVC, PP	75 µm–5 mm	600–2500 MP/m³	Farooq et al. (2023)
	Wastewater treatment plants (WWTP)	Denizli Central WWTP (Turkey)	PE	100–500 µm	4.8×10^6 MP/m³	Koyuncuoğlu and Erden (2023)
Soil	Cropped soil	Zone at Dian Lake (China)	Not reported	00.5–1 mm (fibers)	7100–42,960 MP/kg	Zhang and Liu (2018)
	Vacant land, woodland, and vegetable plots	Suburbs of Wuhan City (China)	PE, PP, PS, PVC	10–100 µm (MP and fibers)	2.2×10^4–6.9×10^5 MP/kg	Zhou et al. (2019)
	Snow and stream	Several sites of Everest (Nepal and China)	PET	18 µm–3800 mm (fibers)	3–119 fibers/L	Napper et al. (2020)
	Agricultural fields	Valencia (Spain)	PP, PVC	50 µm–>1 mm	930–1100 MP/kg	van den Berg et al. (2020)
	Beach sand	33 beaches (Mexico)	PE, PP, PS	0.5–5 mm	31.7–545.8 MP/m²	Alvarez-Zeferino et al. (2020)
	Shade covered soil and open-field agricultural soil	Shouguang City (China)	PP, PE	<0.5 mm (MP and films)	310–5698 MP/kg	Yu et al. (2021)
	Floodplain	Soils of the Lahn River (Germany)	PP, LDPE, PS, PET	2–5 mm	0.4–6	Weber et al. (2022)
	Surface soils and intertidal sediments	King George Island (Antarctica)	PET	<500 µm (MP) and <2000 µm (fibers)	80–740 MP/L 20–80 fibers/L	Perfetti-Bolaño et al. (2022)
	Forests, wetlands, agriculture, and industrial zones	Urban and surrounding areas, Coimbra city (Portugal)	PP, PVC, PE	9 µm–2.94 mm	5000–571000 MP/kg	Leitão et al. (2023)
Air	Outdoors and indoors (active sampling)	Roof building, apartment and office Paris (France)	PP	50–4850 µm	0.3–1.5 fibers/m³ (outdoor) 0.4–56.5 fibers/m³ (indoor)	Dris et al. (2017)
	Atmospheric fallout samples (passive sampling)	Urban dust (China)	PE, PP, PS	200–700 µm (fibers)	175–313 fibers/m² day	Cai et al. (2017)
	Urban outdoor dust	Urban dust (Iran)	NR	100–1000 µm	2.9–20.1 particles/g dust	Dehghani et al. (2017)
	Outdoor in urban and rural areas	Hamburg (Germany)	PE	63–300 µm (MP and fibers)	136–512 MP/m² day (deposition)	Klein and Fischer (2019)

(Continued on following page)

TABLE 1 (*Continued*) Concentrations and type of MP/NP quantified in different environment locations and matrixes.

Matrix/environment		Location/region	Polymer	Particle size of MP/NP	Concentration	Reference
	Indoor and outdoor dust	39 cities (China)	PET, PE, PP	Not reported	1.55–120 mg/g dust (indoor) 0.212–9 mg/g dust (outdoor)	Liu et al. (2019a)
	Indoor dust	Households (Germany)	PET	>100 μm	57 g/kg (textile fibers)	Müller et al. (2020)
	Atmospheric fallout (passive sampling)	Urban dust (UK)	PET	400–500–μm (fibers)	510–925 fibers/m^2 day	Wright et al. (2020)
	Long-term monitoring station	Pyrenees (France)	PVC, PET, PP, PE	<0.45 μm and 10 μm–5 mm	200 mg/m^2 day (deposition) 44–109 mg/m^2 day (deposition)	Allen et al. (2022a)

present in the atmosphere are deposited in quantities of up to 2 × 10^5 ng/m^2 per day, while MPs are deposited in quantities of up to 1.1 × 10^5 ng/m^2 per day, demonstrating that the amount of NPs in the air is higher than MPs. MPs can remain airborne for up to 7 days and reach altitudes of 5,000 km (Allen et al., 2022). MP/NP are also part of the water cycle and are present in rainwater, with great deposition fluxes (Zhao et al., 2023). Brahney et al. (2020) estimated that 1,000 MT of MPs are deposited in the soil of protected areas in the United States after analyzing stormwater and air samples over a 14-month period. It is projected that the amount of MP/NP deposited from the atmosphere will reach 460 MT by the year 2030 (Hundertmark et al., 2023).

Due to their size and resistance to degradation, MP/NP from laundry, household activities, and personal care products containing intentionally added small particles escape from wastewater treatment plants (WWTPs). This is why urban sewers, WWTPs, and water treatment plants (WTPs) are considered one of the main routes of distribution and deposition of MP/NP in oceans, rivers, lakes, subterranean water, soils, and sediments (Browne et al., 2011). A study conducted at 17 WTPs in the United States estimated that effluents can contain and transport up to 13 billion MP/NP per day (Mason et al., 2016). In fresh surface water and groundwater in China and Germany, the presence of MPs ranging from 3–50 μm has been observed, with concentrations of up to 12.6 particles/L (WHO, 2019).

Microplastics/nanoplastics (MP/NP) can be found in drinking water because water treatment plants (WTPs) source water from locations where effluents from wastewater treatment plants (WWTPs) were previously discharged. Studies on MP in water treatment plants in the Czech Republic have shown concentrations of up to 638 particles/L with sizes detected above 1 μm (Pivokonsky et al., 2018). In drinking water from underground sources in Germany, the amount of MP detected has been as low as 0.0007 particles/L with a minimum size of 20 μm (Mintenig et al., 2019). MP/NP can also be found in the drinking water used by industries that utilize plastic equipment and items in their processes. Bottled water from major brands in the market has been reported to contain an average of 325 MP/NP particles of polypropylene (PP) and polyethylene terephthalate (PET) per liter of water sold (Schächtele, 2020). Kosuth et al. (2018) reported the presence of fibers and plastic particles in drinking water and various brands of beer in different countries, with average concentrations of 5.45 particles/L and 4.05 particles/L, respectively. Additionally, Cox et al. (2019) reported that bottled water contains a higher concentration of MP than drinking water due to the detachment of these particles from the container walls.

One destination of WWTPs is the ocean, which can directly receive their effluents or receive them through rivers that previously received them. It has been estimated that more than 1000 rivers polluted with MP/NP flow into the ocean (Meijer et al., 2021). However, it is not the only source of plastic particles. As mentioned above, plastic waste in the oceans also contributes to the generation of these substances. In 2014, it was calculated that there are more than 7,000 tons of plastic waste and over 1.83 billion MP particles dispersed in the oceans (Eriksen et al., 2014), with a large island of these materials floating in the North Pacific Ocean (Onink et al., 2019). Egger et al. (2020) sampled this large island of plastic litter and estimated a presence of up to 3.81 million plastic particles per square kilometer, with sizes ranging from 500 μm to 5 cm, mainly composed of polyethylene (PE) and polypropylene (PP). Correia et al. (2020) estimated that the concentration of particles in the oceans can reach up to 102,000 particles/m^3. This situation indicates a constant increase in the generation of MP/NP due to the degradation of floating macroplastics, which will persist over the years, even if their use is completely prohibited (GESAMP, 2015). Additionally, MP/NP can be dispersed by aerosols from oceanic rainfall and incorporated into the water cycle in other regions (Lehmann et al., 2021)".

According to the World Economic Forum, by 2025, for every three million fish in the ocean, there will be 1 million tons (MT) of plastics, and by 2050, there will be more microplastics (MP) than fish (WEF, 2016). As expected, MP/nanoplastics (NP) have been found in marine species, such as zooplankton, corals, mussels, fish, seagrasses, and crustaceans, which may feed on larger species (Desforges et al., 2015). These marine species become part of the food chain and bioaccumulate these plastic particles in their tissues, transferring them to the next trophic level and potentially entering the human diet. This was confirmed by exposing algae (zooplankton) to polystyrene NP, which were later consumed by water fleas and subsequently fed to fish. All three species bioaccumulated NP in their tissues (Mattsson et al., 2015).

MP/NP can deposit in the soil and have an impact on agriculture. Microplastic causes the destruction of soil structure, destroys microbiota, cause depletion of nutrients, and their absorption by plants decreases plant growth (Bostan et al., 2023). Plastic particles reach farmland through compost materials, plastic films used in agricultural tasks, wind dispersal, but mainly through water and sludge from wastewater treatment plants (WWTPs) and water treatment plants (WTPs) used as fertilizer. Van den Berg et al. (2020) quantified up to 3060 MP per kilogram of soil after being fertilized with sludge from WWTP, with applications of 20–22 tons/Ha. It has been estimated that the amount of MP/NP from WWTP effluents that could be present in farmland amounts to 7.76 million tons (MT) (Peccia and Westerhoff, 2015). MP/NP initially reside on the soil surface and then, due to the penetration of rainwater and irrigation, they are transported to the subsoil and can even reach groundwater (Panno et al., 2019; Wong et al., 2020). Additionally, there is evidence that soil-dwelling organisms, such as earthworms and microarthropods, can transport MP/NP to deeper soil layers or disperse them (Maaß et al., 2017; Rilling et al., 2017). It is estimated that soils contain more MP/NP than oceans, which is concerning as they come into contact with crops that are part of the human diet (Horton et al., 2017; Pathan et al., 2020). Once in the soil, NP with a size of 40 nm can be taken up by plant roots and, to a lesser extent, through leaves, being transported through the plant's tissues. Furthermore, MP/NP can also affect the enzymatic activity of bacteria and fungi and alter their diversity (Bandmann et al., 2012; Sarker et al., 2020; Azeem et al., 2021), in such way that it has been suggested the "plasticsphere" or "microplasticsphere" formation on the soil, which consists of the superficial colonization of plastic waste and MP/NP by cyanobacteria (Nostoc, Scytonema), diatoms (Navicula, Cyclotella) and bacteria (Gammaproteobacteria, Alphaproteobacteria), which can degrade these materials, however, they shift bacterial community and have the potential to alter soil functioning and biogeochemical cycling (Ju et al., 2019; Zhang et al., 2019; Zhou et al., 2021; Behera and Das, 2023).

Another significant but often overlooked source of MP/NP is tire wear resulting from abrasion or friction with the ground when a vehicle is in motion. These particles generated on industrial, urban, rural, or any other roads account for approximately 90% of the total particles found in nearby areas and can reach sizes of up to 280 µm (Kreider et al., 2010; Sommer et al., 2018). Once generated, they are deposited in adjacent territories and can be transported by airborne mechanisms to other locations (Wik and Dave, 2009). Considering that there are approximately 1.446 billion cars in use worldwide as of 2023, the number of tires in circulation is significantly higher. The dispersion pathways of MP/NP are diverse and complex. Once they are swept away or transported by winds, rain, continental and subterranean water, and oceans, they can be found in inhospitable places for human populations. Ubiquitous plastic pollution at macro, micro, and nanoscopic scales even allows us to consider it as a geological marker of human impact on the planet (Geyer et al., 2017).

Damage to living beings

MP/NP are in contact with living beings through different routes: Oral consumption (food), inhalation, and dermal exposure (Revel et al., 2018; Chang et al., 2020). MP has been found in animals and substances (food) that are part of the human diet, such as fish, shrimp, shellfish, honey, sugar, salt, beer, bottled water, and tap water (Liebezeit and Liebezeit, 2013; Auta et al., 2017; Iñiguez et al., 2017; Bessa et al., 2018; Karami et al., 2018; Kosuth et al., 2018). Some studies have estimated the amount of MP consumed by humans. Kieran Cox et al. (2019) reported an intake of 113,743 and 94,283 MP per year in adult males and females, respectively, from food consumption.

NP are potentially more dangerous than MP since they can access cells of many organs due to their size (Monti et al., 2015) by crossing the cell membrane, which has pores of approximately 2–40 nm (Zhou et al., 2009; Bonardi et al., 2011). Once they enter the respiratory system, NP can reach the lungs and subsequently the alveoli. There, they can be transported in the bloodstream and finally deposited in cells of different organs, such as the brain, liver, gallbladder, pancreas, heart, and even the reproductive system and placental barrier (Barboza et al., 2018; Pitt et al., 2018; Hesler et al., 2019; Sökmen et al., 2020).

To this day, there are no studies that clearly or significantly demonstrate the effect of MP/NP on human health due to the difficulty that this implies: all humans are exposed to MP/NP, and it is required to have well-defined groups (control groups), isolating individuals, to know their medical history, long times required, an appropriate sample size, standardized protocols, control of the size and type of MP/NP, and, finally, ethics. However, studies have been reported in animals such as nematodes, crustaceans, fish, and mice (*in vivo* studies) and in cell cultures of various animals (*in vitro* studies), including human cells in relatively short periods of weeks and months (Schröter and Ventura, 2022).

In vivo studies allow the investigation of the effect of MP/NP on an organism by exposing its organs and tissues (at different stages or in its entire life cycle). In marine organisms, MP/NP have been found in feces, gills, skin, muscle, hemolymph, and the circulatory system, causing endocrine disruption, tissue inflammation, behavioral changes, reduced growth, reproductive success, and breeding success (Allen et al., 2022). After an exposure of 10 ppm of PS NP for 120 h, fish embryos have been reported to accumulate these particles in all their organs (mainly in the pancreas and intestinal tract) and are purged when the exposure ends. Interestingly, no evidence of significant mortality, deformity, or bioenergetic changes has been found, but an increase in heart rate and larvae behavior (Pitt et al., 2018). Other studies in fish have shown neurotoxicity, inflammation, or damage in the gut and neurobehavioral alterations, besides NP accumulation in organs (Chen et al., 2017a; Brun et al., 2018; Lei et al., 2018; Sarasamma et al., 2020). In addition to fish, model organisms such as water fleas and nematodes have also been used to assess NP toxicity. Water fleas have shown changes in growth, reproduction, and molting when chronically exposed to 0.1 mg/L of 20–200 nm PS NP (Pikuda et al., 2022). In addition, alterations in the immune system, gene expression, metabolism, and decreased body size have been observed (Liu et al., 2019; Liu et al., 2021). Nematodes have shown reduced pup size, damage in gonad development, inhibition of reproduction, and alteration of locomotion when exposed to 25–100 nm PS NP (Zhao et al., 2017; Kim et al., 2019; Qu et al., 2019).

In vitro studies consist of controlled exposure of NP in cell cultures of various human tissues, such as bronchi, microvascular endothelium, cortical epithelium, monocytes, among others

(Schröter and Ventura, 2022). MP/NP at concentrations of 10 mg/L can induce oxidative stress in human brain and epithelial cells when exposed for 24–48 h (Schirinzi et al., 2017). Other works have reported damage to the mitochondrial membrane, increased apoptosis, activation of autophagy, and inflammatory responses (Wu et al., 2019; Ding et al., 2021; Nie et al., 2021). Some studies of this type contradict each other; thus, it is necessary to clarify whether the type and size of NP can induce effects in different human tissues (Hesler et al., 2019).

The potential damage MP/NP cause is due to the particles themselves and substances with adverse effects that they carry on their surface, such as metals, persistent organic pollutants, antibiotics, pathogens, polychlorinated biphenyls such as pesticides and herbicides, causing synergistic effect (Gewert et al., 2015; Wang et al., 2019; Prust et al., 2020; Ziani et al., 2023). Several authors have reported the combined effects of PM and certain contaminants in the soil, i.e., the accumulation of Deltamethrin and Glyphosate on its surface (preventing or slowing down its degradation and reducing the sorption capacities of the soil), the negative effect on the weight of earthworms due to the glyphosate, the transport of insecticide to deeper soil (Ramos et al., 2015; Yang et al., 2018; Ródríguez-Seijo et al., 2019; Yang et al., 2019). The physicochemical characteristics of PM/NP are important to understand how they can transport harmful substances to living beings and cause a synergistic effect. Among these properties are the polarity, solubility, density, stability, and sorption capacity of the substances.

It has been estimated that 1 g of NP can carry 1–10,000 ng of these toxic substances (Koelmans et al., 2013). Taking into account the impact due to the presence of MP/NP, they can be stored in the intestines of animals and obstruct and change the microbiota, causing imbalances, inflammation, ulcers, and even increasing the risk of cancer (Kirstein et al., 2016; Correia et al., 2020). Some studies report the successful transport of functionalized drugs with biodegradable nanoparticles of different types towards specific organs or tissues (Kotrange et al., 2021; Mitchell et al., 2021), developing the concept of nanomedicine. However, this is a precedent to study the risk in the transport of undesired toxic substances carried by MP/NP, such as bisphenol A, which can be carried by PS NP from the aqueous medium to the brain of fish, affecting dopamine levels, a neurotransmitter that regulates motor activity (Chen et al., 2017b).

Although the effect of MP/NP on human health has not been significantly concluded, MP has been found in several organs and fluids, i.e., in breast milk in 26 out of 34 women who gave birth in Rome. These MP had a size of 2–12 μm and were quantified up to 5 plastic particles per patient, with an abundance of PS (38%), PVC (21%), and PP (17%) (Ragusa et al., 2022). MP up to 10 μm has also been found in human placentas in amounts of 12 particles. The authors assert that these MP entered the bodies of pregnant women through oral or respiratory ingestion (Ragusa et al., 2021). Yan et al. (2022) found MP in the feces of patients with inflammatory bowel disease (IBD) and healthy people, with concentrations of 41.8 MP/g dm and 28 MP/g dm, suggesting that MP exposition could be associated to IBD, or that IBD exacerbates the retention of MP; these MP corresponded to 15 different types of polymers, mainly PET and polyamide in the form of fibers and sheets.

In another study by carried out by Huang et al. (2022), MP with sizes smaller than 500 μm were found in the sputum of 22 patients suffering from different respiratory diseases, indicating that inhalation is a potential way for plastics to enter the human body. In a recent study, Pironti et al. (2022) found four MP in urine of six volunteers (4–15 μm size) with irregular shapes; these fragments were PVC, PP, PE and PVA (Polyethylene vinyl acetate). This preliminary study suggests that MPs could pass through the gastrointestinal tract and are eliminated through biological processes. Leslie et al. (2022) quantified MP/NP up to 1.6 μg/mL in blood from 22 volunteers, with 125–150 μm in size of PET, PE and PS.

International legislation

Legislation regarding MP/NP is undeniably important for reducing and mitigating the impact caused by these materials on ecosystems. Europe and North America have established the regulatory foundations concerning MP. In 2014-2015, the Netherlands banned the addition of plastic particles to products, while the UK followed suit in 2017-2018 (Zhu, 2023). In the United States and Canada, the microparticle or microsphere-free water law was enacted in 2015 and 2017, respectively, which prohibits the manufacture, packaging, and distribution of cosmetics, toiletries, and non-prescription medicines containing particles smaller than or equal to 5 mm. In the United States, this ban came into effect in July 2019 (FDA, 2022), and in Canada in July 2018 (Government of Canada, 2018).

In 2019, the European Union proposed restricting the addition of MP to certain products, and finally, in 2022, they published a draft regulation to prohibit the intentional addition of microparticles of synthetic polymers to cleaners, cosmetics, personal care products, and single-use products (Zhu, 2022). This ban is planned to be implemented within a period of 6–12 years (ECHA, 2023). In China, in 2019, the National Development and Reform Commission stipulated that toiletries and cosmetics containing plastic particles (less than or equal to 5 mm) would be prohibited before the end of 2020, and their sale would be prohibited by the end of 2022 (Zhu, 2022). In Russia, in 2021, the government declared its plans to prepare amendments to legislation to ban the use of single-use items by 2024, aiming to gradually and completely reorganize industrial production with biodegradable products (Korotchenko, 2021). In India, in July 2022, the production, importation, storage, distribution, or sale of some single-use plastic products, ranging from glasses to ice cream sticks, was prohibited, encompassing a total of 19 items in the initial stage (The Associated Press, 2022). In Brazil, there is currently no national law prohibiting the use of single-use items, but since 2020, some cities and states in the country have implemented bans on plastic bags, straws, and other items (Agência Senado, 2021). In Mexico, in 2021, the Senate modified a law with the aim of eliminating the use of plastics by 2025, and concurrently, several state governments have enacted bans on plastic bags and disposable straws (Official Gazette CDMX, 2019; Congress Channel CDMX, 2021).

At the global level in 2022, the United Nations Environment Assembly (UNEA) issued the resolution “the end of plastic pollution,” which seeks to generate specific content for a new treaty through an intergovernmental negotiating committee by 2024 (Li, 2022). In 2019, 187 nations signed an accord called the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal, which restricts participating nations from trading plastic scraps internationally, unless they lack sufficient recycling or disposal capacity. Over the last decade, global plastic trade has indeed declined significantly. However, millions of tons of plastic are still being shipped and mismanaged (WEF, 2023).

Regarding drinking water, bottled water, processed foods, and beverages, the legislation in many countries obligates producers to comply with organoleptic, physical, chemical, and microbiological parameters. It also requires nutritional information on the label. However, these standards do not consider the presence of plastic or foreign particles inside the product as a minimum requirement during processing. The EPA maintains a Contaminant Candidate List (CCL) that includes contaminants that are not currently regulated but are known to be present in public water systems. This list is updated every 5 years, and potential contaminants are regulated once their effects on human health are demonstrated or they are of public interest. Among these candidate contaminants are pathogens, industrial solvents, pesticides, metallic and non-metallic substances, drugs, toxins, among others (EPA, 2023). As of the beginning of 2023, this CCL does not include MP or NP.

Tires and vehicles are significant sources of MP/NP. European legislation considers the raw materials and waste management during tire manufacture, proper disposal at the end of their useful life, and appropriate tire usage (Trudsø et al., 2022). However, this does not guarantee the cessation of MP/NP generation.

As previously explained, current international legislation focuses on avoiding the manufacture of plastic products containing MP/NP or being sources of MP/NP generation. However, the treatment of wastewater containing these materials, their purification before discharging effluents into rivers, lakes, or oceans, air depuration, and food labeling informing the content of these particles have not yet been considered. Furthermore, MP/NP generated from textiles and vehicle tires are far from being addressed within the legislation. Finally, evaluating the risks and toxicity MP/NP pose to human health is essential to establish permissible limits for these particles.

Perspectives: gaps, study opportunities and actions that should be taken

Plastics are involved in all human activities, and due to the amount of commonly used items per person and the increase in the world's population, the impacts of MP/NP are expected to become more evident in the future. While some countries have issued laws or regulations to ban plastic materials (with planned completion within a few years), most of the focus has been on single-use personal care and cleaning products, neglecting clothing, containers, tires, and other items.

The idea of an absolute ban on all plastics in the short term would be inconceivable, as it would lead to a global collapse in clothing, food, and transportation sectors, with immediate effects on health, economy, and the preservation of life as we know it. Plastics have replaced heavy materials that are difficult to manufacture and handle, resulting in lighter equipment and vehicles and increased energy efficiency in the industry. Synthetic fabrics and the manufacturing of clothing have fulfilled the global clothing demand, while the use of medical equipment and single-use plastic instruments has been crucial in surgeries, pandemics, and disease eradication. Therefore, it is unreasonable to consider banning all plastics. Instead, the focus should be on gradually prohibiting only non-essential plastic items, while promoting the development of new single-use materials that are environmentally friendly and do not pose disposal problems (such as Tetrapak).

Finding a solution to this problem is not easy and requires significant economic resources, time, and efforts from authorities, industry, the scientific community, and public participation. Resolving social, political, and economic issues between countries and regions is also necessary. Manufacturing processes and lifestyles must change, from clothing production and consumption to tire and container manufacturing. The scientific community's contributions can be summarized in three main stages: 1) Studying the impact of MP/NP and their synergistic effects with other emerging pollutants on human health, 2) developing treatments or technologies for purifying water, air, and soils contaminated with MP/NP, and 3) developing biodegradable alternatives to plastics that are feasible for the general population. Previous studies and scientific publications related to MP/NP have mostly focused on polystyrene (PS) and the evaluation of MP/NP in marine and freshwater environments, leaving opportunities for further investigation of other MP/NP in the atmosphere and their health impacts. It has been demonstrated that metallic nanoparticles can cross cell membranes, reach the brain, and cause neurotoxicity, increasing the risk of disorders such as Alzheimer's or Parkinson's (Prüst et al., 2020). It is important to assess the risk factors of all types of plastics, analyze and estimate consumption patterns, and develop protocols for detecting these materials in blood, fluids, and feces to evaluate their correlation with disease prevalence or health disorders such as inflammation, ulcers, and thrombosis. More studies are needed to evaluate the interaction between PM/NP and harmful substances for living beings, causing synergistic damage, according to the physicochemical properties of both.

As Wang et al. (2019) demonstrate in their report, there is a lack of studies of MP/NP in soil and airborne; considering airborne and human health risk, several studies could be carried out in large and populated cities; these studies could analyze PM/NP in the air in a passive and active way, even between different nations, which allows elucidating the sources of generation and regional dispersion, and therefore, taking appropriate restrictive or legislative measures in sources that may represent a risk to health jointly between neighboring countries. Another important study opportunity related to the impact on human health is the quantification and characterization of MP/NP at the personal level with personal equipment exposure (carried by people), and the evaluation of MP/NP in the mucosa, so that from the actual concentrations in the air and in the nasal mucosa, the amount of NP that potentially crosses the nasal barriers is estimated. Rahman et al. (2021) collected and characterized MP in air samples by using silver membrane and Teflon filters, finding MP in the respirable size fraction (<2.5 μm); due to several inconsistencies, they suggest the development of new methodologies to collect MP/NP. Regarding indoor MP/NP, home air filtering equipment could be considered to avoid or reduce the intake of PM/NP, since the concentration of these particles is higher indoors than outdoors (Dris et al., 2017; Zhao et al., 2023). In addition, other exposure routes to MP/NP, such as inhalation and dermal absorption should be investigated. Currently, there are no standardized or recommended protocols by the World Health Organization to ensure that drinking or tap water, beverages, processed food and vegetables are free from MP/NP. Several technologies have been published at the laboratory level focus on water treatment, such as ultrafiltration, electrocoagulation and advanced oxidation processes (Thomas et al., 2013; Uheida et al., 2020; Elkhatib et al., 2021; Li et al., 2021; Cuba-Teran et al., 2023), however, these technologies need optimization and implementation in wastewater treatment plants, water treatment plants, and industries.

The sludge from the WWTP used to fertilize agricultural fields must undergo an adequate treatment to separate PM/NP it contains, and avoid its dispersion in soils, sediments, groundwater, rivers and oceans, and most importantly, avoid its dispersion in the human food chain. Unfortunately, air and soil have not been sufficiently studied in different meteorological conditions, so there are opportunities for modeling the trajectories and regional transport of MP/NP in the atmosphere, considering meteorological factors, as well as studying the transport of toxic substances on MP/NP surfaces. Islam et al. (2023) analyzed the MP airborne and deposition within the upper lung airways by using a computational fluid dynamic model, in which they conclude the flow rates, shape, and size of MP influence the deposition pattern, and the higher the flow rate the lower deposition efficiency, however, different shapes and sizes of MP and NP are needed to evaluate. Taking into account industry and its MP/NP emissions to atmosphere, decontamination of MP/NP polluted air could be done by using electrostatic collectors, which are used to separate particulate matter from burned fuels, as Zhao et al. (2023) suggest. Bioplastics or biodegradable plastics offer an alternative to petroleum-derived plastics. However, as discussed in the "origin and formation of micro- and nanoplastics" section, these biomaterials require specific conditions for biodegradation, have low degradation rates, and long degradation times (months). Additionally, natural polymers used in bioplastics constitute only a part of the final product, with the remainder made up of petroleum-derived polymers, making them unfeasible as a standalone solution. In the coming years, it is expected that the industry and the scientific community will develop polymers using truly biodegradable materials in collaboration with authorities to promote campaigns on composting and establish accessible composting centers for citizens. The bio-based plastics of the next-generation must be designed/redesigned considering the tendencies of their polymers to form microplastics, de tal forma que se produzcan la menor cantidad de estas partículas, as Boersma et al. (2023) calculated with the microplastic index, based on the mechanical and properties of the materials.

Despite the existence of bans on certain plastic products, the population continues to use them, and sanctioning the entire community is impossible. Therefore, it is essential for authorities to conduct awareness campaigns regarding the use and impacts of plastics, MP/NP in ecosystems, and the potential effects on human and animal health to encourage commitment and participation from the public. Fighting misinformation, such as the belief that banning plastic bags and straws will solve environmental problems, presents an opportunity for action. Another opportunity is the establishment of institutions or organizations (governmental or private) dedicated to implementing processes for the disposal (recycling) and reuse of plastic waste, processes that are achievable for society, in such way plastic waste avoids landfills, which results in the contamination of soil, groundwater, and surface water (Singh et al., 2023). Finally, the development of a circular economy, where manufactured items do not generate waste and are recycled or reused, is crucial.

Socio-economic aspects to consider to solve the problem

The impact of MP/NP on a country depends on several important factors: The amount of plastics, the facility a person has to generate plastic waste, and its proper disposal. These aspects are interpreted as the amount of plastics produced and used as a result of industrial activities, the number of inhabitants, the quality of life of inhabitants, and the technologies/strategies for waste disposal (Ehrlich and Holdren, 1971). To solve the problem of MP/NP, the proper disposal of plastic waste must be addressed. Therefore, it is useful to consider the social and economic situation of each country. The United States generates about 800 kg of garbage *per capita* per year, of which 130 kg is plastic waste, followed by Denmark, Switzerland, New Zealand, and Hong Kong (Schächtele, 2020; The National Academies of Sciences, Engineering, and medicine, 2022).

The level of industrialization or the economy of countries can be measured by the gross domestic product (GDP), which is an indicator that implies the degree of economic profitability or productivity of a country or area. Meanwhile, the level of development of countries, emphasizing their people and their human wellbeing, can be measured by the human development index (HDI), proposed by the United Nations. The HDI consists of three dimensions: life expectancy, education, and a decent standard of living (UNDP, 2023). This index takes values from 0 to 1, and when it is close to 1, it indicates that the inhabitants and their country are more developed. Table 2 shows the 15 most important economies/countries in 2021 based on GDP, as well as population, HDI, and the generation of mismanaged plastic waste (MPW). MPW is defined as plastic waste that evades its adequate confinement in landfills, incineration, or recycling and ends up exposed in soils and oceans.

Considering the available information from 148 countries (IMF, 2021; World Bank, 2021; World Population Review, 2023; UNDP, 2023) (see Supplementary Table S1), it is possible to reach important conclusions related to economic growth, the generation of plastic waste, and population. By using an association test for these non-normal data, significant correlations were obtained for several scenarios (Table 3). A positive correlation was found between GDP and MPW, interpreted as a developed country generating more waste, while MPW and HDI were negatively correlated, suggesting that higher human wellbeing of inhabitants is associated with lower generation of MPW. It must be noted that these two associations were weak, with coefficients of

TABLE 2 Population, human development index and mismanaged plastic waste of the 15 countries with the highest gross domestic product.

Country	GDP (billion USD)	Population	HDI	MPW generation (million ton)
United States	23 315	331 894 000	0.921	267.4
China	17 759	1 412 360 000	0.768	12 272.2
Japan	5 005	125 682 000	0.925	35.6
Germany	4 262	83 196 000	0.942	50.6
India	3 150	1 407 564 000	0.633	12 994.1
UK	3 123	67 327 000	0.929	29.9
France	2 957	67 750 000	0.903	27.7
Italy	2 115	59 110 000	0.895	38.8
Canada	2 001	38 246 000	0.936	23.5
Russia	1 836	143 449 000	0.822	363.3
Brazil	1 648	214 326 000	0.754	3 296.7
Australia	1 646	25 688 000	0.951	5.2
Spain	1 428	47 416 000	0.905	20.3
Mexico	1 272	126 705 000	0.758	430.6
Indonesia	1 187	273 753 000	0.705	824.2

GDP, Gross domestic product; HDI, Human development index; MPW, Mismanaged plastic waste. Available data from 2021 (IMF, 2021; World Bank, 2021; UNDP, 2023; World population review, 2023).

TABLE 3 Spearman coefficients of MPW correlated to GDP, population and HDI.

MPW vs.	GDP	Population	HDI
Coefficient	0.4099	0.7891	−0.4548
p-value	0.0000	0.0000	0.0000

0.4099 and −0.4548, respectively. Finally, the most significant correlation was found between the population of countries and MPW in the environment (coefficient 0.78), suggesting that the number of people in a country could have a greater impact on MPW generation than economic and industrial activities. The countries that generate the most plastic waste are also the most populated, such as China, India, and Brazil, with 12.2, 12.9, and 3.2 MT of MPW, respectively (World Population Review, 2023).

Worldwide plastic production reached 390.7 MT in 2021, with China as the main producer, accounting for 32% of the total, followed by North America and the European Union with 18% and 15% respectively (Plastics Europe, 2019). It is necessary to clarify that leading countries in plastic manufacture do not necessarily generate MPW or contribute to MP/NP generation in their territories, but rather in the countries to which they export the raw material or finished products.

Among the strategies to dispose of plastic waste are recycling, incineration, and landfills (the latter contaminating other matrices). Globally, it has been estimated that only 9% of plastic waste is recycled, 19% is incinerated, 49% is confined in landfills, and 22% is misdisposed. North American and European Union countries use landfills to dispose of up to 82% of their plastic waste. On the other hand, the most populated countries and some others in Asia, Africa, and Latin America misdispose up to 64% (OECD, 2019), indicating that they lack adequate waste disposal strategies. A secondary strategy to dispose of plastic waste is its commercialization, which facilitates the management of large amounts of plastic waste through exportation. However, when unusable plastic waste is imported, both the Industry and the importing country face disposal complications. Europe is a leader in the importation/exportation of plastic waste, with an importation of 2.8 MT in 2022 (WEF, 2023).

In developing countries, where basic needs for food, safety, housing, and even clothing have not been met, policies and strategies for solving environmental problems take a secondary place. This hypothesis is confirmed by the negative association between MPW and HDI in Table 3. As a reflection of these scenarios, in Latin America, Africa, and many Asian countries, there are no adequate waste management programs or plans, including for plastics. With the foregoing, it is fair that developed countries and transnational companies that have historically polluted and impacted ecosystems and human health should take the lead in strategies against MP/NP, followed by the rest of the world.

Conclusion

International legislation plays a crucial role in reducing and mitigating the impact of microplastics and nanoplastics (MP/NP) on ecosystems. Despite its progress, there are significant gaps in current legislation. Wastewater treatment, purification of effluents, air depuration, and food labeling regarding MP/NP content have not been adequately addressed. Furthermore, the legislation lacks specific regulations for MP/NP generated from textiles and vehicle tires. To effectively address the issue of MP/NP, three main areas of focus are required: Understanding the impact of MP/NP on human health, developing purification technologies for contaminated water, air, and soil, and promoting the development of biodegradable alternatives to plastic. The issue of MP/NP requires a multidisciplinary approach involving collaboration between authorities, industry, the scientific community, and the general public. The scientific community should conduct further research on the health effects of different types of plastics, including ingestion, inhalation, and dermal absorption. Standardized protocols for detecting MP/NP in biological samples (animals and humans) should be established, and the risk factors associated with MP/NP exposure should be assessed. Current regulations related to drinking water quality should consider MP/NP as contaminants, as well as efforts should be made to develop and implement technologies for the detection and removal of MP/NP from drinking water sources. Additionally, more research is needed to understand the presence and transport of MP/NP in the atmosphere, as well as the potential risks associated with inhaling these particles. Socio-economic factors play a significant role in plastic waste generation. The most populated countries contribute to plastic waste generation in their own territories, on the other hand, developed and industrialized countries are leaders in plastic manufacturing. All of them contribute to MP/NP generation, nevertheless, developing countries face challenges in implementing waste management strategies due to limited resources and competing priorities. International cooperation and support from developed countries and transnational organizations are necessary to assist developing nations in improving waste management practices.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2023.1241939/full#supplementary-material

SUPPLEMENTARY TABLE S1
Socio-economic data.

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