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Review article

Microplastics in Ecuador: A review of environmental and health-risk assessment challenges

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ABSTRACT

Pollution from plastic debris and microplastics (MPs) is a worldwide issue. Classified as emerging contaminants, MPs have become widespread and have been found not only in terrestrial and aquatic ecosystems but also within the food chain, which affects both the environment and human health. Since the outbreak of COVID-19, the consumption of single-use plastics has drastically increased, intensifying mismanaged plastic waste in countries such as Ecuador. Therefore, the aim of this review is to 1) summarize the state of MP-related knowledge, focusing on studies conducted with environmental matrices, biota, and food, and 2) analyze the efforts by different national authorities and entities in Ecuador to control MP contamination. Results showed a limited number of studies have been done in Ecuador, which have mainly focused on the surface water of coastal areas, followed by studies on sediment and food. MPs were identified in all samples, indicating the lack of wastewater management policies, deficient management of solid wastes, and the contribution of anthropogenic activities such as artisanal fishing and aquaculture to water ecosystem pollution, which affects food webs. Moreover, studies have shown that food contamination can occur through atmospheric deposition of MPs; however, ingredients and inputs from food production, processing, and packaging, as well as food containers, contribute to MP occurrence in food. Further research is needed to develop more sensitive, precise, and reliable detection methods and assess MPs' impact on terrestrial and aquatic ecosystems, biota, and human health. In Ecuador specifically, implementing wastewater treatment plants in major cities, continuously monitoring MP coastal contamination, and establishing environmental and food safety regulations are crucial. Additionally, national authorities need to develop programs to raise public awareness of plastic use and its environmental effects, as well as MP exposure's effects on human health.

Abbreviations: BPA, bisphenol A; CPE, chlorinated polyethylene; EDCs, endocrine-disrupting chemicals; HDPE, high-density polyethylene; LDPE, low-density polyethylene; MSW, municipal solid waste; MPs, microplastics; NPs, nanoparticles; NOAA, National Oceanic and Atmospheric Administration; NY, nylon; PA, polyamide; PAAm, polyacrylamide; PE, polyethylene; PET, polyethylene terephthalate; PL, polyester; PP, polypropylene; PS, polystyrene; PTFE, polytetrafluoroethylene; PU, polyurethane; PVC, polyvinyl chloride; UNEP, United Nations Environment Program; WWF, World Wildlife Fund for Nature.

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1. Introduction

One of the biggest challenges currently facing the world is waste generation, particularly contamination from domestic and industrial waste and its treatment. As part of this problem, an exponential increase in plastic production has led to widespread plastic accumulation in the environment [1], which constitutes a high proportion of municipal solid waste (MSW) [2]. Plastics have become ubiquitous in human daily life because of their low manufacturing costs and advantageous physiochemical characteristics, including durability, lightness, chemical resistance, and ability to be used at a variety of temperatures [1,3]. However, plastics' durability and relative non-biodegradability have become an alarming problem; instead of decomposing completely, plastic gradually breaks into smaller and smaller pieces [4] that spread throughout the air, soil, surface, and groundwater [5]. Further, the COVID-19 pandemic substantially increased medical waste, especially that of single-use plastics; for example, an estimated 1.56 million face masks entered the ocean in 2020 [6], and a single disposable surgical mask can release up to 6.4×10^8 microplastics (MPs) fibers from natural weathering [7]. Peng et al. [6] used an ocean model to quantify the pandemic's impact related to plastic waste and determined that by the end of the 21st century, almost all pandemic-associated plastic will end up in either the seabed (28.8 %) or on beaches (70.5 %).

Inefficient and inaccessible MSW services are a problem in many regions, including Latin America [3]. In areas of Asia, Western Europe, Latin America, the Middle East, Japan, and Central Europe, 9 %–12 % of MSW constitutes plastic, which often ends up in landfills or the oceans [8]. Indeed, according to the United Nations [9], plastics represent 85 % of the waste originating from land that reaches the oceans.

The investigation of MP presence, abundance, and distribution in Latin America is limited, leading to knowledge gaps in certain regions [3,10]. Brazil, Chile, and Mexico have the highest output of scientific publications, but countries such as Peru, Argentina, Colombia, Uruguay, Costa Rica, Ecuador, Cuba, Jamaica, Honduras, and Trinidad and Tobago contribute a much lower scientific production [7]. Several studies have been performed in coastal areas of Latin America and the Caribbean where the widespread MP contamination is attributed to high population density locations without proper collection of domestic wastewater and mismanaged waste, which might cause the entry of plastic debris and MPs into terrestrial and aquatic compartments [11–14].

Along coastal areas of Ecuador, the presence of plastic debris and MP contamination have been reported in the Galápagos Islands [15–17]. However, tourism has increased in recent years, where cities such as Quito or continental coastal provinces (Esmeraldas, Manabí, and Santa Elena) with the largest number of tourist beaches in the country have also been affected by litter [18]. On the other hand, Quito, Esmeraldas, Guayaquil, and Riobamba, among other cities of Ecuador, discharge industrial and household wastewater without prior treatment, affecting rivers and reaching the Pacific Ocean [13,19,20]. To date, information on plastic debris or MP contamination in areas of Ecuador such as the Galapagos archipelago, northern coast, or Amazon region is still scarce.

Because of plastic materials' long durability and the fragmentation processes of MPs and NPs, it is important to understand their presence, mobility, potential environmental effects, trophic transfer, and exposure-related health problems. Hence, this review aimed to collect existing literature on MP contamination in Ecuador to 1) summarize the state of knowledge, focusing on studies conducted with environmental matrices, biota, and food, and 2) analyze the efforts by different national authorities and entities in Ecuador to control MP contamination.

2. Data sources

Due to the limited data from studies conducted in Ecuador, this review included information from 17 potentially relevant peer-reviewed studies and 8 Bachelor's theses (in English and Spanish) related to MP presence in the environment, marine biota, and food (see Supplementary Table 1). Mendeley software (https://www.mendeley.com) was used to manage the bibliography and its references, and seven major databases—Directory of Open Access Journals, Science Direct, Web of Science, Food Chem, Latindex, ResearchGate, and Google Scholar—were searched.

3. Origin and classification of microplastics

Unlike polymers of natural origin such as cellulose, starch, lignin, and natural rubber, plastics are synthetic chemical substances [21]. These are classified according to their size: macroplastics (>20 mm), mesoplastics (5–20 mm), MPs (<5 mm), and nanoplastics (NPs, <1 nm) [22–24]. Plastics of all sizes undergo biological and chemical degradation processes (corrosion, photo-oxidation, ocean temperature), as well as physical degradation from various environmental factors or weathering processes, including abrasion, erosion, wave action, wind, and fragmentation from ultraviolet radiation [25–27]. This fragmentation causes irregular instead of uniform particle shapes, normally rounded but also plate, bar, and irregular (amorphous) [28,29], associated with intentional production [30]. The most common MP forms are classified as granules, fibers, fragments, films, strings, sponges, microspheres or microbeads, foams, pellets, and flakes [31,32].

Regarding origin, MPs are commonly divided into two groups. Primary MPs are mainly micro-sized plastic beads and industrial production pellets (<5 mm) or powders (<0.5 mm) used in cosmetic products and household and commercial goods. Fibers from synthetic textiles and clothing (nylon, polyester, polyurethane, polyolefin, acrylic, and vinyl-type polymers) are also considered primary MPs. Secondary MPs are derived from the fragmentation and degradation of large plastic waste [25,31].

Plastic debris and MPs include materials with a wide range of chemical compositions and characteristics that affect their end point in the environment. Since MPs have a large surface-area-to-volume ratio and surface hydrophobicity, they interact with organic matter, inorganic elements, and microorganisms in aquatic habitats, as well as absorb various toxic environmental contaminants and transport them within and between different habitats [3,26]. The plastic debris that most produces MPs are polypropylene (PP), polyethylene (PE), low-density polyethylene (LDPE), high-density polyethylene (HDPE), polystyrene (PS), polyvinyl chloride (PVC), polyethylene terephthalate (PET), polyamide (PA), and polymeric polyurethane (PU) [26,33,34]. In addition, polyester, which largely comprises PET and constitutes 70 % of fiber production (polyester/polyamide/acrylic), contributes to 92 % of the plastic generated annually [35]. Nylon (NY), another type of plastic, is the generic name for synthetic polymers made up of polyamides, which can be processed into fibers, films, or shapes, and is widely used for fishing nets and lines [21,36].

4. Presence and distribution of microplastics

All products from plastic fragmentation, including MPs and NPs, are ubiquitous and persistent [25,37,38]. Previous studies have demonstrated the presence of these pollutants in remote and pristine areas, including Arctic sea ice and at the bottom of the Mariana Trench [39–41]. Studies have also confirmed that MPs impact communities and ecosystems geographically distant from their source [33,42], as well as trophic transfer within food webs [43–47].

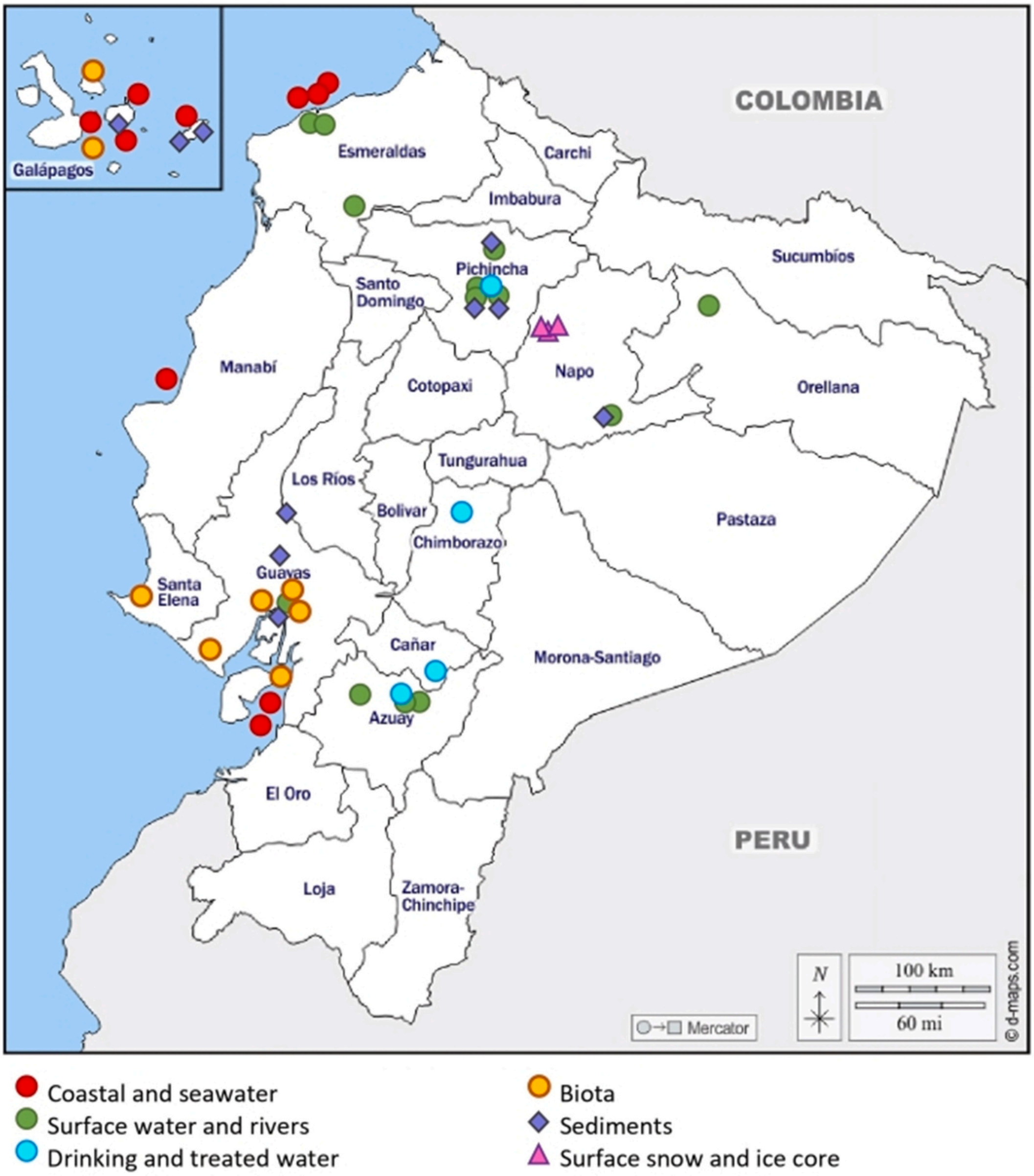

Fig. 1. Geographical location of the microplastic-related studies conducted in Ecuador on different matrices. Resource: Free maps by https://d-maps.com/carte.php?num_car=3402&lang=es.

Note: Food and beverages were not considered in the map, since samples obtained for these studies were purchased on markets along the country, and its production location is unknown.

The extensive distribution of MPs in aquatic and terrestrial environments, including air, water, sediment, and marine organisms, indicates the different pathways for MP exposure, such as food products and drinking water. This exposure can result in various human health effects from ingestion or inhalation [48–51].

Fig. 1 shows the regional distribution of microplastic-related research conducted in Ecuador, according to the different matrices assessed using the information detailed in Supplementary Table 1.

Studies were mainly concentrated in aquatic systems (46 %), followed by biota (22 %), while food and beverages (8 %) each were the least studied (Fig. 2). On the other hand, most shapes of MPs observed were fragments, fibers, and films, with variable polymeric composition (Fig. 3).

4.1. Plastic occurrence in aquatic systems

Most MP-related water pollution comes from improperly disposed-of land-based plastic waste [25,37,38], domestic and industrial wastewater discharge, and discarded derivatives from marine activities such as plastic fishing equipment [12]. MPs are also in cleaning and cosmetic products [32] as small, fragmented plastics called "microbeads." As sewage treatment plants cannot filter MPs or microbeads, these contaminants enter marine and freshwater environments, including coastlines, oceans, deep-sea sediment, bays, lakes, rivers, ponds, and even remote, pristine areas [1,26,32,44]. It has been reported that over 300 million metric tons (MMT) of plastic is manufactured annually, 50 % of which is indiscriminately disposed of into the environment, and approximately 4.8–12.7 MMT enters the aquatic ecosystem [27].

High levels of MPs and microbeads have been found in Antarctic and Arctic waters and the deep Arctic seafloor; these act as an additional global sink of plastic [52]. MPs have been found in the digestive tracts of fish [53,54] and seals [53,55], demonstrating that MPs in marine habitats are easily ingested by a wide variety of organisms, ranging from zooplankton to whales [56].

Meanwhile, the composition of MPs and NPs (i.e., PE, PP, PS, PVC, PU, PA, and PET) affects their deposition, suspension in the water column, and ability to float. PE materials usually sink below the upper-surface water, while materials such as plastic films, polyester resin, and soft drink bottles tend to sink to the bottom [32]. Further, oceanic gyres act as convergence zones, where plastic debris accumulates in subsurface and surface water due to ocean circulation [15,57]. The North Atlantic gyre has the highest concentration of plastic, at 20,328 (±2324) pieces.km^{-2} [54,57]. In the South Pacific subtropical gyre, approximately 26,898 particles. km^{-2} ranging in size from 0.355 mm to over 4.750 mm have been found [52].

In Latin America, MP assessment in aquatic systems from countries such as Argentina [58], Brazil [59,60], Colombia [61–63], Chile [64], Mexico [65,66], and Paraguay [67], has been increasingly documented. Fisheries, agricultural practices, raw wastewater outflow, household activities, industrial effluents, tourism, and terrestrial litter inputs, were identified as the main MPs sources.

In the Tropical Eastern Pacific and Galapagos Islands in Ecuador, a Marine Protected Area, Alfaro-Núñez et al. [15] found MP particles in 100 % of the analyzed ocean water samples, reporting the highest concentration (μp.m^{-3}) for the smallest particle size

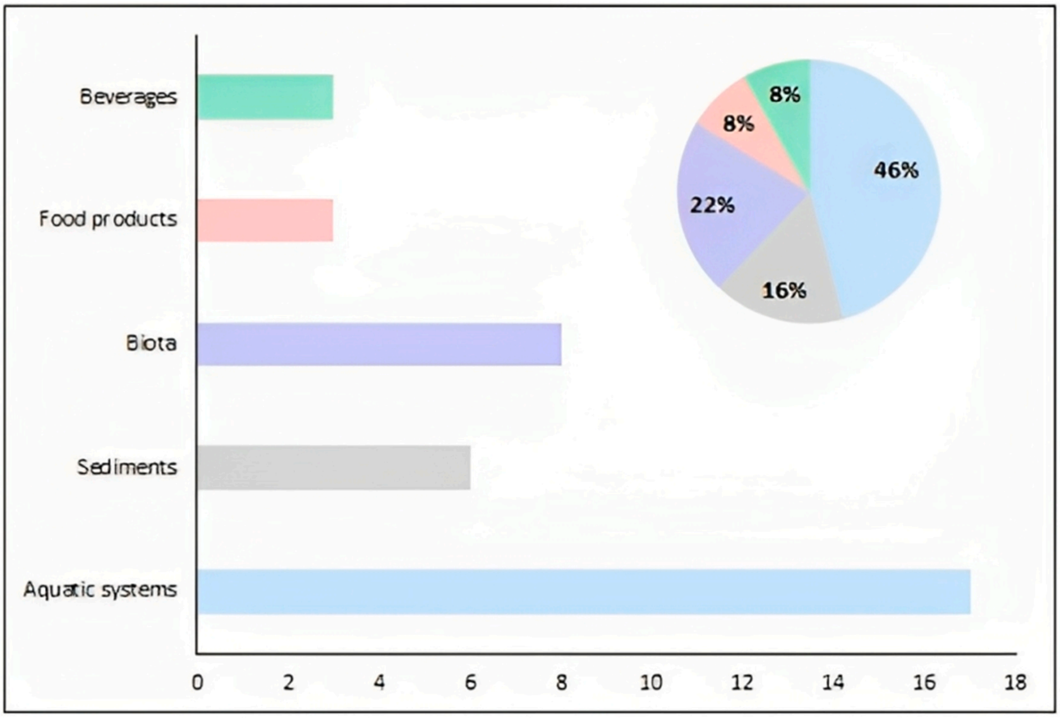

Fig. 2. Number of studies reviewed according to the classification of topics: aquatic systems, sediments, biota, food, and beverages.

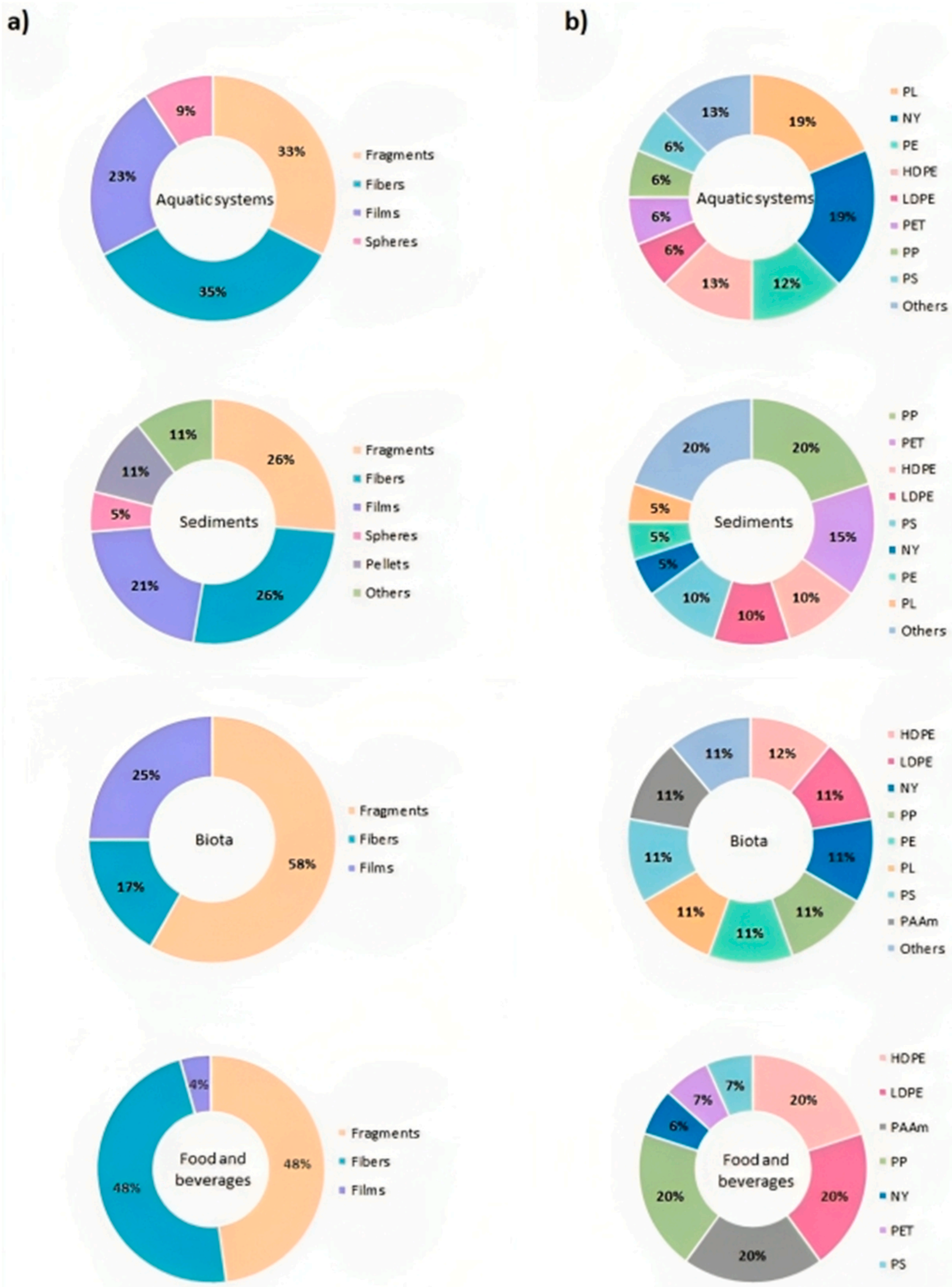

Fig. 3. Percentage of predominant (a) shapes and (b) polymers of microplastics-related studies on the different matrices.
Note: HDPE: high-density polyethylene; LDPE: low-density polyethylene; NY: nylon; PA: polyamide; PAAm: polyacrylamide; PE: polyethylene; PET: polyethylene terephthalate; PL: polyester; PP: polypropylene; PS: polystyrene; Others (CELL: cellulosic; CPE: chlorinated polyethylene; PTFE: polytetrafluoroethylene; PU: polyurethane; PVC: polyvinyl chloride).

category (150–500 μm). Jones et al. [68] also reported seawater surface contamination due to MPs around the coast of San Cristobal in the Galapagos Islands, with a concentration of 0.89 particles·m^{-3}, with a major contribution of PP and PE fragments (32 %). This content might be attributed to the local inputs such as wastewater outfalls, boat activity, and surface runoff, because of promoted tourism and the large population in the area.

In other Marine Protected Areas from Latin America, high concentrations of MPs have been found in surface waters from Rio Lagartos coastal lagoon in Mexico (1.51 particles·m^{-3}) [69], and the Itaipu Embayment in Brazil (2.9 particles·m^{-3}), where HDPE was the most frequent polymer (38 %), followed by PP (21 %) [70].

In these cases, anthropogenic activities influence the abundance and distribution of MPs, however, it was also demonstrated that oceanographic, meteorological, and environmental conditions affect its presence in different areas. The low content of MPs in surface waters from the Galapagos Islands in comparison to other polluted areas in Latin America, seems like the prevailing equatorial current carries floating MPs away from the Galapagos [71]. However, according to Zachello Nunes et al. [72], even Marine Protected Areas cannot be effectively protected against MP pollution.

In the continental northern coast of Ecuador, in Esmeraldas Province, Capparelli et al. [19] suggested that macroplastics and MPs reach the coastal area of Esmeraldas after being transported by sea currents and not necessarily from continental pollution. For instance, Garcés Ordoñez et al. [62] carried out a study in the coastal surface waters of the Colombian Caribbean and Pacific, where the Tumaco sampling station, near the northern boundary with Ecuador, showed MP concentration between 0.06 and 2.99 particles·m^{-3}. This area has the highest production of wastewater and solid waste with inadequate management, affecting rivers, estuaries, and coastal marine environments.

Another pathway of MP environmental pollution is through sewage water, which is discharged into rivers as effluent or incorporated into sludge. Sewage sludge enters freshwater environments and coastal sediment, causing direct and indirect adverse effects on aquatic biota [73–75].

In urban areas in Ecuador's Andean region, rivers provide water for agriculture and human consumption, but wastewater treatment is limited. In Quito, the capital of Ecuador, less than 10 % of the wastewater is treated; the rest is dumped into rivers untreated [13]. In the Guayllabamba River, Donoso and Rios-Touma [13] found 1584.23 MP m^{-3} in water, showing the presence of MP fragments, films, and fibers, which are transported along the river. In this case, fibers were the most abundant particles related to synthetic clothing products and laundry. They also found that urban areas had the highest MP amounts, while the basin headwaters, which are far from urban areas, had the lowest. In other Andean area in Latin America, Martínez Silva [61] determined MP concentration in the surface water of the Magdalena River that flows through Neiva, Colombia. Results showed that MP concentrations increased with downstream distance and areas with higher population, ranging from 97 to 135 fibers·m^{-3}, where municipal activities such as wastewater outflow and laundry washing contributes to MP deposition into the river water.

In Ecuador, water sources for drinking water are mostly superficial: rivers and reservoirs [20], and MPs can reach reservoirs and creeks via water and air currents. Paredes et al. [20] found MPs in 19 % of the collected samples in the drinking water system of Riobamba, in the Ecuadorian highlands. Fibers between 0.49 mm and 4.29 mm were detected in drinking water reservoirs. In another study on the water treatment system and distribution network in the city of Cuenca, Ecuador, which supplies 90,000 families in the city, 99 water samples were analyzed. MP fibers and fragments were found, with an average of 73.12 particles·L^{-1}, ranging in size from 6.31 to 4966.77 μm for fibers and 6.95–243.87 μm for fragments [76]. On the other hand, in the water network system of Azogues, approximately 338 particles·L^{-1} were found in residential tap water, where fibers were the most abundant (176.4 particles·L^{-1}), with sizes between 1.33 and 4988.73 μm [76]. The presence of MPs has also been detected in drinking water from residential and commercial areas of Brasilia, Brazil, where 100 % of samples contained MPs fragments, 48 to 1194 MPs·L^{1}, with a ranging size of 6–50 μm [77].

Thus, although MPs have been identified in different water resources such as rivers and potable water systems, treatment of drinking water to reduce consumers' MP exposure is still lacking in some developing countries, including Ecuador. Furthermore, wastewater treatment is also needed, as polluted water from upstream flows into water drainage areas and eventually reaches the Pacific Ocean, threatening sensitive ecosystems like mangrove forests and the Galapagos Islands [13,16].

4.2. Microplastics in sediments

Approximately between 60 %–80 % of plastic debris from land-based sources, ends up being deposited on beaches or floating in coastal waters [10,17]. Across Latin America, several studies have been carried out on beaches mainly from Brazil, however more studies in the coastline regions of Ecuador, Colombia, Peru, Chile, and Argentina, among others, are still needed [3,10].

Within studies along the Pacific coast, the mean abundance of MPs found on popular sandy beaches from Lima, Peru was 174.1 ± 44.8 particles·m^{-2} [78], while Purca [79] reported a mean of 129.8 particles·m^{-2} in the same area. On the other hand, in isolated beaches from the South Pacific coast of Chile, an average abundance of 27 particles·m^{-2} was found, nevertheless in the Easter Island the reported abundance was higher than 800 items·m^{-2} [80]. The transport of plastic debris in the ocean due to the South Pacific Subtropical Gyre can explain the accumulation of MPs on the beaches of the Easter Island [80]. However, the distribution and concentration of MP in coastal and marine environments take place because of the interaction of different natural and anthropogenic processes that control the input and transport of these particles from their sources to their deposition sites [10].

In Ecuador, specifically in two islands of the Galapagos archipelago, Santa Cruz and San Cristobal, a high concentration of MPs was found in the sea turtle nesting zones perpendicular and parallel to the waterline, respectively [17]. The mean concentration of MPs in Tortuga Bay (Santa Cruz island) was 74 ± 43 particles·m^{-2}, with the predominant presence of PE polymers (69.2 %). On the other hand, in Punta Pitt (San Cristobal island), MP mean content was 381 ± 68 particles·m^{-2}, five-fold higher than at the strandline in Tortuga Bay, and particle composition was mainly PE (64.45 %) and PP (31.6 %). Fragments and pellets were the most abundant particles according to their shape, suggesting that finer-scale currents and prevailing winds may impact the fragmentation of plastic debris and its local distribution patterns, whereas, pellets are being transported up the beach, perhaps due to their rounded nature, which affects native species [17]. A study carried out in a touristic area in Cartagena Colombia, showed the presence of plastic pellets on the sandy surface of the beach, parallel to high-tide lines, with mostly polymer composition of PE and, in some cases, PP [81]. Acosta-Coley and Olivero-Verbel [81] also suggested that pellets can easily travel long distances due to tides, currents, and winds, making them excellent transport links for the spread of nonnative species to various ecosystems.

Freshwater and marine environments are also considered as sinks of MPs, as they can be drawn down into the deep-water column and even deposited in sediments. Sedimentary MPs can be transported together with sediments along rivers to oceans, or resuspended and transported by hydraulic forces [82]. MPs in river sediments in Latin America have been scarcely assessed.

In the coastal region of Ecuador, the Guayas province is highly industrialized and it is mainly influenced by agriculture, aquaculture, navigation, among other anthropogenic activities that have impacted the Guayas Basin, representing an important source for plastics and MPs discharges into the SE Pacific Ocean [83,84]. In sediments at the strandline of Los Tintos and Vinces rivers which flow into the Guayas estuarine system, the most frequent MPs shape were fibers and fragments [84], while in downstream sediments from Isla Santay in the estuary of the Guayas River, films were the most abundant [83]. The fragmentation of single-use plastic products as packaging and bags might be related to MP pollution in both areas. According to the National Institute of Census and Statistics of Ecuador (INEC), it is estimated that 12,739 tons of garbage are daily thrown away, of which 11.43 % corresponds to single-use plastic (531,461 tons) such as bags and food containers [83]. Common polymers identified in plastics as PP, PET, PS, HDPE, and LDPE are used in plastic bottles, food containers, blister packs (medicine packaging), drainage pipes, containers, and shower curtains, which are products that are easily found in solid household waste [85]. In a study carried out in sediments of the Jurujuba (Guanabara Bay) and the Itaipu embayments in the southeastern region of Brazil, seven different types of synthetic polymers were found in sediment samples [70]. Fibers and fragments were the dominant MPs, and the polymeric composition of HDPE and PP was the most found, coinciding with the consumption pattern in the world [70].

To date, there is an evident knowledge gap on MPs occurrence in sediments from Andean freshwater systems in Ecuador. In Quito, Ecuador, in the upper Guayllabamba River Basin, the number of MPs (14.3–186.5 items·kg^{-1}) were highly correlated to the concentration of pollutants in water at downstream areas, mainly with the increasing industrialization and population density [13]. A similar situation was reported by Shruti et al. [86], where MPs from the Atoyac River Basin, a highly urbanized river system located in Central Mexico showed that the concentration of MPs in sediments was higher in the downstream section of the river (833–900 items·kg^{-1}) due to the dense population and industrial complex of Puebla City. Even though, in the Atoyac River Basin, there is a relatively high number of wastewater treatment plants along the area, in comparison to the limited water treatment plants in Quito, it is evident that the population density and industrial activities have a significant effect on the widespread distribution of MPs in freshwater systems.

It has already been demonstrated that the most downstream sites will receive the greatest amount of MP inputs from all sources upstream [13,61,86], however, more studies are needed to fill the knowledge gap in the distribution of MPs in freshwater environments of Latin America [3].

A study of the beach on the Puerto Misahualli River, which is part of the upper Amazon River system in Ecuador, found an average of 987 particles·kg^{-1} of dry sediment with MPs between 0.5 and 2 mm and 761 particles·kg^{-1} of dry sediment with 5 mm > MPs >2 mm [87]. The MPs were likely deposited in beach sediment due to occasional flooding and hydrological influence at the watershed outlet. In other tributaries of the Amazon River in upstream and downstream areas from the metropolitan region of Manaus, Brazil, concentrations of MPs in the riverbed sediments ranged from 0 to 5725 particles·kg^{-1} of dry sediment with sizes between 0.063 and 1 mm, and from 417 to 8178 particles·kg^{-1} of dry sediment with MPs from 0.063 to 5 mm [88]. The region of Manaus is one of the most industrial and technological parks in Latin America with more than 600 factories from different segments, while Puerto Misahualli is a nature-oriented tourist area with discharges of untreated water from domestic sewage systems and mismanagement of solid waste along the hydrographic basin. In both Amazon areas, it has been shown that MPs can be transported downstream for long distances and accumulate in the riverbed or floodplain along the Amazonian wetlands.

MPs can also enter terrestrial ecosystems via the application of biosolids, the use of compost and organic fertilizers, plastic film mulching, and atmospheric deposition. In these cases, synthetic fibers and tire particles are the main sources of MPs, which reduce soil quality [89,90]. Additionally, the use of sewage sludge to fertilize soil and wastewater for irrigation increases soil MP contamination. It has been reported that the use of sludge in agriculture adds 125–850 tons of MPs per one million inhabitants to European soil annually [90]. The effect of sewage sludge on horticultural productivity has also been examined. For example, tomato plants exposed to sewage sludge containing up to 31,100 particles·kg^{-1} (dry weight) slowed the plants' growth and productivity and delayed fruit production [91].

Moreover, MPs in soils can be taken up by plants and transferred along the food chain [92]. However, current knowledge of MPs in soil is very limited, and thus more studies are necessary to determine soil pollution levels and assess ecological risks.

Studies performed in Latin America have shown that MPs can also be accumulated over time in soils with different land use systems [7]. The frequent application of sewage sludge, compost manure, wastewater, and contaminated irrigation water to farmlands increase the MPs content in soils, leading to the formation of different shapes and compositions of plastic [93,94]. Lastly, to the best of our knowledge, no microplastic contamination studies in soils have been conducted in Ecuador.

4.3. Air as an exposure avenue for microplastics

Where airborne MPs come from and where they end up has been poorly documented. However, it has been demonstrated that air is a major MP source in urban environments, as they are released from vehicle abrasion (tire-tread wear), construction activities, synthetic fibers from clothing and houses, wind-blown plastic debris from landfills, waste incineration, and road devices like traffic cones, barrels, and speedbumps [95,96]. MPs can be transported by wind to pristine, remote environments [97,98], distant terrestrial and aquatic ecosystems [99], and deposited on surfaces in cities or agrosystems, affecting terrestrial organisms and water sources [96].

In a riverside urban site in central London, Wright et al. [97] found MPs in atmospheric samples, with deposition rates ranging from 575 to 1008 MP $m^{-2}\cdot d^{-1}$. Moreover, Dris et al. [100] found synthetic fibers in indoor and outdoor air in sampling sites located approximately 10 km from Paris, France; indoor concentrations ranged between 1.0 and 60.0 fibers$\cdot m^{-3}$, while outdoor concentrations were significantly lower, between 0.3 and 1.5 fibers$\cdot m^{-3}$. Other results reported by Gaston et al. [99], Klein and Fischer [101], and Vianello et al. [102] confirmed the ubiquitous presence of MPs in indoor and outdoor air environments.

Scarce studies have been carried out in Latin America's metropolitan areas. Among these, in populated cities such as Mexico City and São Paulo, atmospheric MP concentrations in PM_{10} and $PM_{2.5}$ were found [103,104]. In outdoor air samples from both cities, fibers, and fragments were the most common shape, >75 % and >64 %, respectively. In Mexico City, polymers such as cellophane, PE, and PET were identified, while in São Paulo, PL fibers, PE, and PET particles were dominant. Degradation of tires from road friction has been reported as a significant source of MPs in airborne [103–105], nevertheless, abrasion of synthetic clothes or textiles, household objects, electric clothes dryers, coats of paint, also contributes to air pollution [104].

Urban pollution, human activities, and dense population are associated with the MP widespread in megacities. However, meteorological conditions such as weather variation, seasons, rainfall, relative humidity, and wind velocity can influence the abundance of MPs in some areas [103,104]. Shruti et al. [103] showed that MPs in Mexico City are more abundant during the dry season due to the probable weathering caused by UV radiation and high temperatures in the absence of rain, facilitating long-distance transport and deposition of suspended MPs in the environment.

In Ecuador's northern Andes cordillera, surface snow samples from 5000 to 5400 m above sea level from the Antisana glacier showed that air masses can transport and deposit MPs on surface snow. The results also demonstrated that MPs in the glacier may have been transported westward across the Amazonia Basin [106].

So far, investigations on airborne MPs have been limited around the world. Further research is needed to determine the distribution and residence durations of MPs in the atmosphere under local conditions, as there is a significant influence of MPs on locations far from their pollution sources, functioning as a vector for their introduction into different ecosystems [103,107]. Moreover, inhalable MPs might depend on their size, where small fibers can probably penetrate the airways and affect human health [97,101,103,104].

4.4. The presence of plastic particles in biota

According to the marine food web, zooplankton are a pathway for MPs, threatening the health of marine biota [108,109]. In the northeast Pacific Ocean, Desforges et al. [108] identified MP ingestion rates via zooplankton of 1 particle per every 34 copepods and 1 particle per every 17 euphausiids. MPs have also been found in filter-feeding organisms (e.g., mussels, oysters, and clams), which are the second most studied group of aquatic organisms [56]. For example, MP presence was investigated in two species of commercially grown bivalves, *Mytilus edulis* and *Crassostrea gigas*; an average of 0.36 ± 0.07 particles$\cdot g^{-1}$ (wet weight) and 0.47 ± 0.16 particles$\cdot g^{-1}$ (wet weight), respectively, were found [32]. As mentioned, ingestion of MPs occurs within several trophic levels, eventually reaching fish species [110] and marine mammals [111] affecting over 1200 marine species [112]. Additionally, trophic transfer of MPs increases MP bioaccumulation in top predators, including humans, which poses a risk to human health from whole-seafood consumption [53,113,114].

Plastic particles have also been found in the stomachs of seabirds such as fulmars (*Fulmarus glacialis*) and flesh-footed shearwaters (*Ardenna carneipes*) [112,115]. Indeed, Charlton-Howard et al. [112] reported the sub-lethal "hidden" impacts of plastic ingestion by the latter species: for the first time, "plasticosis," which is a fibrotic disease developed in response to plastic exposure, was found in seabird stomach tissue.

In Latin America, MP contamination in individuals of different species has been investigated mostly in Brazil, Argentina, Colombia, and Chile, focusing more than 99 % on fish species, with less than 1 % on others like seal, bivalve, snail, crab, and shrimp [3]. Studies have shown that planktivorous fish possibly mistake MPs for food because of their similar appearance and same size scale, leading MPs to enter and be transferred along marine food webs [60,110,116].

Along the coasts of Panama, Colombia, Ecuador, Peru, and Chile, from 292 planktivorous fish captured, only 6 individuals (2.1 %) contained MP particles in their digestive tract [110]. However, on the Pacific coast of Ecuador, Alfaro Nuñez et al. [15] found that 63 % of planktivorous species (240 marine organisms including fish, cephalopods mollusks, and crustaceans) presented MP pieces in their digestive tract. A significantly higher content than the previous study by Ory et al. [110].

Other studies carried out on species from different trophic levels, such as benthopelagic stingrays from the Brazilian Amazon Coast [117], benthic organisms, Ascidiacea and Amphipoda, in Ilha Grande Bay, Brazil [118], and carnivorous fishes from the Amazon River and the Santa Marta Estuary in Colombia [119,120] showed MP in the gastrointestinal tracts with variable frequency of occurrence. PET, PA, and PE were the most frequent polymers found among the studies, showing consistency with the main sources of plastic contamination of river basins and, eventually, oceans. The textile industry, including clothing, bottles, degradation of fishing gear, such as ropes, and nets, fishing and aquaculture activities, domestic discharges, among others, contribute to the entry of MPs into the ecosystems [117–120].

Few studies have been done in Ecuador on MP presence in biota. Villegas et al. [84] assessed MP content in the tissue of fiddler crabs *Leptuca festae* and *Minuca ecuadoriensis* from Isla Santay, a Ramsar site in the Guayas River estuary. The results showed the highest concentration of MPs in their gills, which is related to these crustaceans' chronic contamination exposure. Aguirre-Sánchez and Purca [121] reported the presence of MPs in crabs (*Ucides occidentalis*) in Tumbes, northern Peru. MPs were identified in 100 % of the samples, finding 475 items (52.57 %) in the gills, and 446 (48.43 %) in the digestive tract. Results indicated that benthic organisms consume plastic debris accumulated in the bottom of mangroves.

In another study, plastic debris was found in the stomach contents of Humboldt squids (*Dosidicus gigas*) caught in the ports of Manta and Santa Rosa de Salinas; 12 % of the stomachs contained plastic remnants [122]. On the other hand, in squids bought in market ports in four provinces (El Oro, Santa Elena, Manabí and Esmeraldas), Alfaro Nuñez et al. [15] found 93 % of MP prevalence in its digestive tract, suggesting the squids directly ingest plastic. Montenegro Solórzano [123] also found pieces of plastic debris in the digestive tract of *Coryphaena hippurus* (31.4 %) and *Sarda orientalis* (25.3 %). Thus, there is evidence of plastic pollution in marine environments in Ecuador, which may affect the ecosystem's trophic web [122]. Far away from the Ecuadorian coasts, in the Eastern Pacific Ocean, 139 MP were extracted from the gill, esophagus, stomach, intestinal tract, and muscle in 15 wild-caught dolphinfish (*Coryphaena hippurus* L.) suggesting that the exposure of pelagic fish species to MP pollution involves toxicological impacts on fish and beyond on human health [124].

Regarding bivalves, the presence of MPs was confirmed in *Mytella guyanensis*; samples from three sites in Puerto El Morro, Guayas, indicated MP presence in aquatic organisms was associated with nearby urban population activities such as fishing and aquaculture [125]. Further, MPs in the digestive tracts of different pelagic and demersal fish species have also been identified [126–128]. Plastic fragments, films, and fibers were found in samples captured in coastal areas of Ecuador (Guayas and Santa Elena provinces), where untreated domestic, agricultural, and industrial wastewater is discharged, and anthropogenic activities such as artisanal fishing and aquaculture are carried out, contributing to water ecosystem pollution [129].

Microplastic uptake by invertebrate benthic organisms in the intertidal rocky zone from Lima, Peru, was studied. Three specimens of mollusk species, *Semimytilus algosus*, *Tegula atra,* and *Chiton granosus* were sampled. *C. granosus* had the highest MP content (6.92 ± 2.13 particles·g^{-1}), followed by *S. algosus* (1.65 ± 0.22 particles·g^{-1}), and *T. atra* (0.88 ± 0.20 particles·g^{-1}), showing that filter feeders are the most vulnerable species to MP pollution in the marine environment as they ingest a greater number of particles [130]. Accumulation of MPs by oysters (*Crassostrea brasiliana*) and mussels (*Perna perna*) in a highly urbanized estuarine system of Brazil has been also assessed [131]. The highest MPs levels reported for mollusks to date were found in *C. braziliana*, with 44.10 particles·g^{-1}, showing that oysters and mussels are suitable as sentinels, reflecting the gradient condition for other contaminants as PAHs, organochlorine compounds, toxic metals, and marine litter, in the region [131]. Moreover, the occurrence of MPs in many shellfish can cause adverse effects on the organisms themselves, including physical blockage of the gut, decreased filtration rates and energy availability, reduced larval development and fecundity, as well as induced oxidative stress and genotoxicity. This raises potential health risks to higher trophic levels of organisms, including humans [132].

Ecuadorian studies have also focused on birds. In a suburban waste dump in Calceta, Manabí Province, 112 pellets from black vultures (*Coragyps atratus*) were analyzed [133]. MPs were identified in 81 % of the samples, among other anthropogenic materials such as glass, synthetic rubber, and cardboard. As per Richard et al. [133], plastic ingestion affects the mortality rate of birds, including condors and vultures, as anthropogenic materials are eaten indiscriminately.

As evidenced above, most MP-related studies have focused on the marine environment, which means there are severe knowledge gaps regarding the terrestrial food chain and related human MP exposure [3,11,134,135]. As of writing this article, no studies on terrestrial organisms in Ecuador were found.

4.5. Plastic particles in food and beverages

Studies have reported that MPs can be transferred from marine sources, such as seafood and sea salt, to humans through the food chain [136–138]. However, MPs have also been detected in other foods, such as table salt [138–141], sugar [142,143], beer [141,144], soft drinks [145], honey [143,146], canned food [147,148], infant formula [149], and milk [135]. MP food contamination can also come from external pollution sources such as atmosphere deposition, considering MPs' presence in indoor and outdoor air. MPs have also been detected in human feces, confirming their ingestion [150].

Other external contributors to MP contamination of food are plastic packaging materials [150,151]. In a study of PP, PS, PE, and PET take-out containers by Du et al. [150], MPs were found in all sampled containers and ranged from 3 to 29 items per container. They simulated various eating conditions including direct flushing, flushing after immersion in hot water, flushing after microwaving, and flushing after refrigeration. Results showed that the major sources of MPs were: 1) the loose structure and rough surface of PS containers, which are likely to release more MPs; and 2) atmospheric fallout and particles flaking from the container's inner surface. Approximately 2977 MPs may be ingested through take-out containers per person per year, which is similar to the intake via food [150]. Other studies have reported different amounts of plastic particles consumed from various food products: 11.6 billion particles released from a single plastic teabag at a brewing temperature of 95 °C [152]; 1000 MP particles each year from table salt [140]; and 11,000 MPs per year in shellfish [153]. Further, although MP food contamination is a universal problem, the COVID-19 pandemic increased the demand for packaged food products [154]; thus, further research focusing on MPs in various food packaging and their translocation and accumulation within the human body is needed.

To the best of our knowledge, in Latin America, investigations of MPs in food and beverages have only been conducted in Mexico and Ecuador [3]. The study of MPs in Ecuador is still in its early stages. Concerning MPs in food, analysis has been carried out on honey, beer, milk, shrimp, and tuna [155–157]. In a study carried out in Singapore, on shrimp imported from Ecuador and sold in local markets, Curren et al. [157], showed that film MPs were the most abundant (93 %), followed by fragments (4.7 %), fibers (2 %) and spheres (0.3 %). Similarly, in the northern Bay of Bengal along Bangladesh's coast, two species of shrimp corresponded to 57 % and 32 % of ingested MPs, respectively, which were mostly fibers [114]. Further, because shrimp are typically eaten without deveining them first, humans are more exposed to MPs, as they can be transferred via the food chain increasing the impact on human health.

MP pollution in beers from Mexico and Ecuador had the highest content, 152 particles·L^{-1} and 46.5 particles·L^{-1}, respectively, while soft drinks showed lesser MP amounts (40 particles·L^{-1} and 32 particles·L^{-1}, respectively) [145,155]. In the case of milk samples, MPs in bottled or packed milk have been less examined [158]. Kutralam et al. [135] and Diaz Basantez et al. [155] reported that fibers and fragments comprised the largest amount of the total detected MPs. MP contamination can be attributed to operation and production processes or even to packaging materials used in the bottles and caps [145,155].

Finally, studies in Ecuador have suggested that the ingredients and inputs during food production, processing, and packaging and via food containers contribute to MP presence in food. For example, in beer, soft drinks, and water-packed tuna, the water is considered the main MP source [155,156]. In Quito, Kosuth et al. [141] reported a maximum of 9.04 particles·L^{-1} in 24 samples of drinking water. They also analyzed tap water samples from 14 countries, finding that 81 % of samples contained anthropogenic particles; most of these particles were fibers (98.3 %) between 0.1 ± 5 mm in length.

However, more studies are needed to encourage national authorities to establish relevant regulations.

5. Human ingestion of MPs and associated health effects

Because of the considerable amount of plastic waste already present in marine environments, not only do animals become entangled in large pieces, causing injury and even death [41,159], but fragmented plastic particles can be broken down to the same size as plankton and grains of sand, making them accessible to various organisms through different feeding strategies [160]. Ingestion of MPs by marine organisms can cause damage at the cellular, tissue, organ, and organismal levels, including DNA damage; inflammatory responses; hepatotoxicity; improper gill functioning; intestinal tract blockage; accumulation in the gills, gut, and liver; inhibition of gastric enzyme secretion; reduced feeding stimuli; decreased steroid hormone levels; delays in ovulation and failure to reproduce; and mortality [25,56,161]. Studies have reported that MPs ranging in size from 0.1 to 150 μm can be transported by the circulatory and lymphatic systems, but that they do not penetrate deeply into organs and are likely eliminated via the spleen [37,162]. It has also been found that MP ingestion by mice affects the intestine, which showed an inflammatory response, decreased intestinal mucus secretion, and damage to the intestinal barrier function, leading to more gut mucosa permeability, among other consequences [37,162,163]. Furthermore, the accumulation of MPs (<5 mm) in fish intestines can result in starvation malnourishment, and ultimately death [52].

One major concern is the potential fragmentation of MPs into nanoparticles. Unlike MPs, NPs (<100 nm) can penetrate all organs, including the human placenta, as well as the blood–brain barrier [25, [preprint] [164–169]] and the gut epithelium (likely via the M-cell-rich Peyer's patches), resulting in systemic exposure. Walczak et al. [170] demonstrated through an in vitro model simulating human digestion that 50-nm polystyrene nanoparticles can cross the epithelial intestinal barrier. Further, paracellular transport has been observed in particles up to 150 μm in organs such as the liver. However, phagocytosis and endocytosis could occur with particles >0.5 μm and up to 0.5 μm, respectively [37,171].

Plastic particles exhibit toxicity as their size decreases; nevertheless, it has also been reported that harmfulness depends on surface functionalization, exposure time, and dose [37,172]. Accumulation and absorption of MPs can cause serious health effects such as oxidative stress, disturbance of energy and lipid metabolism, neurotoxic responses, DNA damage, immune responses, metabolic disruption, increased cancer risk, cell damage, tissue inflammation respiratory, and neurodegenerative diseases [25,44,168,169,172,173]. However, MPs' toxic effects and their implications for humans have not yet been fully explored, and more research on human health risks is needed [37,44].

A study by the World Wildlife Fund for Nature and the University of Newcastle showed that, on average, a person ingests approximately 5 g of plastic per week through water and food. Depending on consumption habits, the estimated MP ingestion per week can reach 1769 particles in drinking water, 182 in crustaceans, 10 in beer, and 11 in salt [41]. Additionally, MPs are present in the atmosphere and transported by wind, further contaminating marine and terrestrial environments [163]. Airborne plastic particles are breathed in by humans and have been observed in pulmonary tissue [174], producing lung inflammation. Although mucociliary clearance in the upper respiratory tract prevents larger particles from entering the human airway, plastic particles can still penetrate the deep lung and be retained by physiological fluids [25,174]. MPs can also pass through cell membranes, causing respiratory irritation, dyspnea, coughing, increased phlegm production, asthma, oxidative stress, cancer, and cardiovascular diseases [25,175].

As mentioned, the main pathway for human plastic exposure is the consumption of contaminated water or food (principally fish, shellfish, and commercial salt), but airborne MP exposure is also highly likely [25,37,44,48,50,168,176]. Beyond the problems caused by MPs physically present in the body, studies have also shown that hazardous additives in plastics tend to leach out into aquatic environments, releasing environmental pollutants such as metals, pharmaceuticals, pesticides, and persistent organic compounds. Chemical contaminants and even human pathogens can also be absorbed by MPs, which act as physical and chemical stressors or vectors, entering the human digestive, respiratory, and circulatory systems [50,177].

Additives in plastics include pigments, dyes, inert or reinforcing fillers (e.g., clays, silica, glass, chalk, talc, asbestos, alumina, rutile, carbon black, and carbon nanotubes), plasticizers, antioxidants, UV stabilizers, lubricants, anti-static and foaming agents, flame-retardants, phthalates, nonylphenols, and bisphenol A (BPA), among others, which improve plastic's physical and processing properties [37,45,160,172,177]. These additives are not always chemically bound to the plastic polymers (except for some flame-retardants) [177]. Adverse health effects from additives include reproductive toxicity, carcinogenicity, and mutagenicity [37,48,174]. Among the most common plasticizers are phthalates, which have been classified as endocrine-disrupting chemicals (EDCs) and linked to respiratory problems (asthma and allergies, especially in children), breast and skin cancer, obesity, insulin resistance, type II diabetes [178], and in utero biological effects [179,180]. Phthalates are rapidly metabolized in the body and excreted in biological fluids such as urine [181,182] and breastmilk [178,183,184]. Another plastic additive and common EDC is BPA, which affects reproductive organ development; respiratory, hepatic, and renal functions; and can lead to cancer, among other disorders [185,186]. A European Union report showed that from 2005 to 2018, over 1500 cases of harmful phthalates were reported in various products (89 % of Chinese origin), mostly toys (94 %) [177]. In addition, the chemical decomposition of certain polymers may also produce toxic substances; for example, PVC contains a carcinogenic monomer and several hazardous additives, likely making it the most toxic plastic [48]. Polybrominated diphenyl ethers (PBDEs), which are used as flame-retardants, may cause long-lasting behavioral abnormalities, particularly in motor activity and cognition [187].

Finally, some toxic trace metals (As, Sb, Sn, Zn, Pb, Cr, Co, Cd, and Ti) are used as stabilizer additives in polymer products, whose presence and accumulation in the body directly expose consumers and possibly affect human health. According to the International Agency for Research on Cancer, As, Cd, Cr, Pb, and Hg are classified as potential human carcinogens; their toxicity depends on many different factors, including dosage, exposure route, and chemical species [177].

Although exposure to plastic particles and their additives through the food chain and their adverse human-health effects are expected to be low and very difficult to assess [38], further investigation is needed because of the lack of information on food content, MP, and additive toxicity for wildlife and humans, and subsequent dietary exposure [37].

6. Ecuadorian legal and scientific framework

Presently in Ecuador, contaminant-associated health-risk assessment falls under a traditional framework based on contaminant quantification and comparison with the maximum permissible thresholds established by national or international standards. However, this practice is unsuitable for complex or even simple mixtures of pollutants that can interact among themselves and with the environment. Further, MPs and NPs do not easily fit within traditional risk-based regulatory frameworks due to their persistence and extremely diverse sizes, shapes, chemical properties, absorption/desorption processes, and heterogeneous occurrence in the environment [188,189]. This complexity requires open collaboration between all possible actors, including scientists, regulators, and legislators, to establish effective guidelines for contamination and exposure [188].

Currently, there are no universal legal policies [190,191] for pollution caused by MPs and NPs [163,192].

However, different regions and countries have established or implemented regulations to ban the production and use of primary MPs [1,163]. Considering MP accumulation and the complexity involved in data assessment, regulatory agencies are taking a more cautious approach, classifying MPs as *non-threshold contaminants* for risk assessment purposes [188,192].

To mitigate MP- and NP-related environmental and human health impacts, various international government agencies have implemented strategies [188,191] such as reducing or prohibiting single-use plastics; improving waste storage, disposal, and collection systems; encouraging infrastructure improvements and technological innovation; and decreasing global plastic production [190,191, 193]. In the last decade, the United Nations Environment Program (UNEP) and the Marine Debris Program of the National Oceanic and Atmospheric Administration (NOAA) have collaborated to prevent, reduce, and abate the ecological, human health, and economic impacts of marine debris worldwide [190,191]. In addition, since its establishment in 1974, the UNEP Regional Seas Programme has provided inter-governmental frameworks to protect marine environments. Within this context, the UNEP Regional Seas Programme and the Global Programme of Action for the Protection of the Marine Environment from Land-based Activities are leading the response from the United Nations Environment Assembly resolution on marine plastic debris and MPs [194].

The European Union requires member states to reduce plastic bag use and control and reduce marine litter [195]. Similarly, in 2015, the United States passed the Microbead-Free Waters Act, prohibiting the use of plastic microbeads in cosmetic manufacturing, packaging, and distribution [1]. The French and Thai governments have also banned the sale of cosmetic products containing microbeads, while China and New Zealand banned the addition of solid plastic particles to personal care products [196].

Although some policies and regulations regarding macroplastics have been established, unified and integrated mechanisms and laws are needed to regulate and control the spread of MPs and NPs in the environment [190]. However, there are several programs to protect areas such as Antarctica [197], the Caribbean [198,199], the Pacific Islands [200,201], and the Baltic Sea region [202]. Unfortunately, the existing agreements are insufficient, and areas beyond national jurisdiction, where no nation is responsible for surveillance, monitoring, and management, constitute 64 % of the ocean surface [188,203].

Currently, there are no specific policies and regulations targeting MPs in Latin America [7]. Therefore, generating more studies and knowledge on microplastic occurrences is important to seek the attention of authorities in developing Latin American countries to establish public policies and regulations, and improve waste management strategies in the control and mitigation of MP contamination in the region [3,11,12].

Particularly in Ecuador, to date, there is no specific legal framework to control MPs and NPs and prevent possible risks. However, in 2020, the legislature passed the Organic Law for the Rationalization, Reuse, and Reduction of Single-Use Plastics [204,205]. The Ecuadorian government will implement programs, policies, and actions under this law considering its main aims: 1) progressively reducing single-use plastics at the source; 2) promoting reduced waste-related pollution and plastic waste in water systems and national protected areas; 3) encouraging the population to reduce plastic waste by reuse and recycling or industrialization; 4) replacing single-use plastics with recycled or biodegradable materials with a smaller carbon footprint [204].

In addition, MPs and NPs have not been identified as contaminants in the Ecuadorian regulations for the processing of food and beverages such as alcoholic [206] and non-alcoholic beverages [207–210], and salt [211]. These emerging pollutants have been found in low concentrations in natural liquids (milk and honey) and in other liquid foods available in Ecuadorian markets that require water as a raw material, like beer and soft drinks [155]. In the case of foods of natural origin, such as seafood, the Codex Alimentarius [212] is used as a reference for threshold values. Nevertheless, it does not contain maximum values for MPs or NPs.

7. Research gaps and future directions

Despite numerous existing studies related to MPs, there are still some gaps in knowledge due to the subject's complexity and MPs' potential interactions and decomposition-associated by-products [38,44,213]. Although several studies have provided methodologies to determine these, they have certain limitations. First, the standardization of MP monitoring methods is essential to be able to compare studies and increase risk assessment reliability [214–216]. Second, several techniques are needed to ascertain the potentially toxic compounds that constitute the materials [188,217].

In certain cases, economic, technical, and technological limitations, mainly in developing countries such as Ecuador, may result in the omission of certain components. These "blind spots" may impair the overall risk assessment and require further investigation before guidelines or regulations can be established. However, at the same time, researchers must continue to develop more sensitive, precise, and reliable analytical detection methodologies [168,215]. Additionally, international, and national policies must remain open to improvements in evidence-based methodologies as the science progresses and, above all, extend their application to all possible MP sources.

Government control agents must consider every component of MP contamination process to have evidence of the possible environmental and health hazards of the materials and their components. With this data, the government can apply restrictions, regulations, or policies regarding plastic manufacturing and use as well as identify and prioritize MP sources, end points, transport, and exposure pathways that must be controlled. Additionally, technological support should be developed for effective monitoring [188].

The high occurrence of plastic products already in the environment and the knowledge gaps related to MP uptake and transport and their real, long-term effects on ecosystems and human health require the implementation or improvement of plastic waste management [213]. Indeed, in the last few years, there has been a cultural shift in how plastics and all their associated negative effects, mainly on marine life, are perceived. However, despite this greater awareness and desire to lead more sustainable lifestyles, more studies and incentive-based policies and regulations are required to facilitate human behavior change regarding the use and disposal of plastic materials [1].

8. Conclusions

To date, a very limited number of studies have been conducted in Ecuador to determine MP content in food and environmental matrices. Most of the research has focused on the surface water of coastal areas. Ecuador has insufficient wastewater management policies, deficient solid waste management, and poor water resource administration [13]. For example, less than 10 % of the polluted water in Quito is treated, albeit barely; the rest of the untreated sewage ends up in the Guayllabamba River, which flows into the Esmeraldas River and then into the Pacific Ocean [218]. Many methods for both identifying and quantifying MPs have been applied; however, given the complexity of these emerging contaminants (considering their diverse sizes, shapes, polymer types, and associated monomers), more studies are needed to not only have reliable, precise, sensitive, and standardized identification and measurement methodologies for different matrices but also to explore their potential environmental and health-related effects. The complexity of MPs' chemical characteristics and their tendency to interact with multiple toxic contaminants in the environment increases the magnitude of the possible effects on aquatic and terrestrial ecosystems, biota, and human health, which necessitates further research worldwide. Additionally, in Ecuador specifically, wastewater treatment plants in major cities, continuous monitoring of MP coastal contamination, and the establishment of environmental and food safety regulations are key. Moreover, national authorities must develop different programs to raise public awareness of problems related to plastic use and the MP-related effects on the environment and human health.

Finally, it would be important that national authorities encourage research on MPs to develop strategies and control these emerging pollutants.

Data availability statement

Data will be made available on request.

CRediT authorship contribution statement

Pamela Y. Vélez-Terreros: Data curation, Investigation, Methodology, Writing – original draft, Writing – review & editing. **David Romero-Estévez:** Investigation, Methodology, Writing – original draft, Writing – review & editing. **Gabriela S. Yánez-Jácome:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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