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Pathways of human exposure to microplastics, and estimation of the total burden

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Plastic production is continuously growing and their wastes contaminate practically all environmental niches. In the environment, large plastics undergo continuous degradation processes generating a broad amount of microplastics and nanoplastics (MNPLs) that spread through air, land, and seas. Thus, humans suffer chronic exposures to MNPLs through different pathways: ingestion, inhalation, and dermal contact. Here, we have reviewed the recently published data regarding human exposure to MNPLs. The total load of plastic particles that humans are exposed to has been estimated based on these newly reported studies. This analysis of novel literature shows that despite ingestion is the most studied route of exposure, other routes of contact with MNPLs should not be underestimated. At the same time, gaps regarding the investigation of human exposures to environmental MNPLs have been detected, as well as the lack of robust and standardized protocols, operating procedures, and methodologies to detect/quantify MNPL in human/biological matrices.

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Introduction

The word plastic is a term used to describe a wide range of synthetic or semisynthetic materials. Plastics are made of organic compounds such as cellulose, carbon, natural gas, salt, or petroleum. Since 1855, when the first synthetic plastic material (known today as celluloid) was created, a wide variety of plastics has been developed until these days. Innovation in plastic materials continues to grow and thanks to its characteristics that include low-cost production, high durability, and versatility, they stand out as attractive materials for multiple applications in different areas such as product packaging, construction, and building, automotive, mechanical engineering, agriculture, medical applications or electronics, among many others. Depending on its properties, plastic materials can be classified into different groups: bioplastics, biodegradable plastics, technical plastics, epoxy resins, expanded polystyrene (EPS), fluoropolymers, polyolefins, polystyrene, polyurethanes (PUR), polyvinylchloride (PVC), polyethylene (PE), and polypropylene (PP) among others [1]. From large pieces of these plastics, microplastics and nanoplastics (MNPLs) originate either in a targeted manner by an industrial process, or due to a natural continuous process of aging and degradation into the environment. Depending on such origin, they are classified into primary and secondary MNPLs, respectively [2]. The continuous degradation of plastics results in mixtures of MNPLs with a wide range of sizes. While the term nanoparticle, and therefore the term nanoplastic, is well-defined as sizes ranging from 1 to <100 nm by the International Organization for Standardization [3,4], no formal size definition is available for microplastics. Although microplastics should be formally defined as plastic particles ranging from 1 to 1000 μm, considering the conventional units of size and their nomenclature, as recommended by Hartmann *et al.* [2], there is a lack of consensus on the size limits. Thus, the limit size for microplastics is often defined for convenience according to the sampling method. The Joint Group of Experts on the Scientific Aspects on Marine Environmental Protection (GESAMP), consider microplastics as particles from 1 nm to <5 mm since they were pragmatically defined as particles under 5 mm at the first international research workshop on the occurrence, effects, and fate of microplastic marine debris celebrated in 2008. This definition was established taking into account the inclusion of particles that can be ingested by biota, as well as those particles that can present properties different from those of macroplastics [5]. In this way, most of the studies consider 5 mm as the upper limit size of microplastics since the biological effects and properties of those particles are different from those found for large pieces of plastic. In this review, we refer to microplastics in the broad sense of the definition, as proposed by GESAMP, and not in a strict and literal sense of the definition of the word microplastic. We assume that this pragmatic use of the term microplastics can mask their potential biological effects since they are strongly associated with the size. At the nanosize, nanoplastics can be more easily uptake and distributed in cells, tissues, and organs than microplastics. Thus, size is an important factor modulating the harmful effects of MNPLs [6].

Plastic in different environmental matrices

Only during 2018, 359 million tons of different plastic materials were produced in the world and many of them were used to produce one-use goods, becoming waste after its short/useful life. Moreover, most of the plastics manufactured for different applications are not biodegradable. As a result, plastic waste accumulates in both landfills and the other environmental compartments. Although the trend to recycle plastic is indeed increasing, 25% of the plastic post-consumer waste ended up in landfills in 2018. Of this, an unknown amount of plastic post-consumer waste that is not collected generated by littering and unauthorized dumping must be added [7]. All that plastic debris ending in different environmental matrices translates into contamination supposing a great environmental challenge.

The amount of plastic found in the different environmental matrices is the sum of macroplastics and MNPLs that arrive from different sources of contamination, and those MNPLs that are formed *in situ* by the degradation from larger pieces of plastic. In the environment, plastic materials are exposed to either microbial degradation [8,9] or different weather and environmental conditions such as UV radiation, oxidants, rainfalls, and winds among others [10,11]. In general, both abiotic and biotic pathways lead to a great formation of MNPLs.

Regarding the amounts present in different environments Jambeck *et al.* [12] calculated that from 275 million metric tons of plastic waste generated in 192 coastal countries, from 4.8 to 12.7 million metric tons entered in the oceans from land in 2010. Moreover, they predicted that the amount of waste entering into the ocean from the land would increase by one order of magnitude by 2025. In the oceans, different garbage patches are found and they remain to accumulate plastic debris rapidly. For example, the Great Pacific Garbage Patch placed between California and Hawaii contains 45–129 thousand tons of plastic floating in an area of 1.6 million km^2. In that area, microplastics account for 8% of the total mass but 94% of the estimated 1.8 (1.1–3.6) trillion pieces floating in the area [13]. Most of the plastic transported from land to oceans travels through rivers, and there is evidence of MNPLs in rivers worldwide [14]. It has been determined that the most relevant source of river contamination are wastewater treatment plants [15]. Likewise, contaminated freshwater flows back to the terrestrial environment through different land use as agriculture, urban or parks, and recreation areas [16].

On the other hand, pieces of evidence of MNPLs on airborne have been reported recently [17]. These MNPLs suspended in indoor and outdoor air are the result of daily actions such as opening a plastic package, microfiber detachment from textile garments, or the wear of vehicle tires, all contributing to the particulate matter in ambient air [18–20]. Through atmospheric deposition, these particles arrive at land, aquatic environments, or even to remote locations where MNPLs have been found in snow from very different sites [21].

Soil ecosystems have received less attention in comparison with aquatic ecosystems. Nevertheless, apart from atmospheric deposition, MNPLs enter soil through many other sources: landfills, compost and organic fertilizer, wastewater-irrigation, land application of sewage sludge, or agricultural residuals [22–24]. Furthermore, it has been reported that MNPLs can be transported from the soil surface to deeper layers by earthworms, making it accessible to soil biota and even with the possibility to reach groundwater [25].

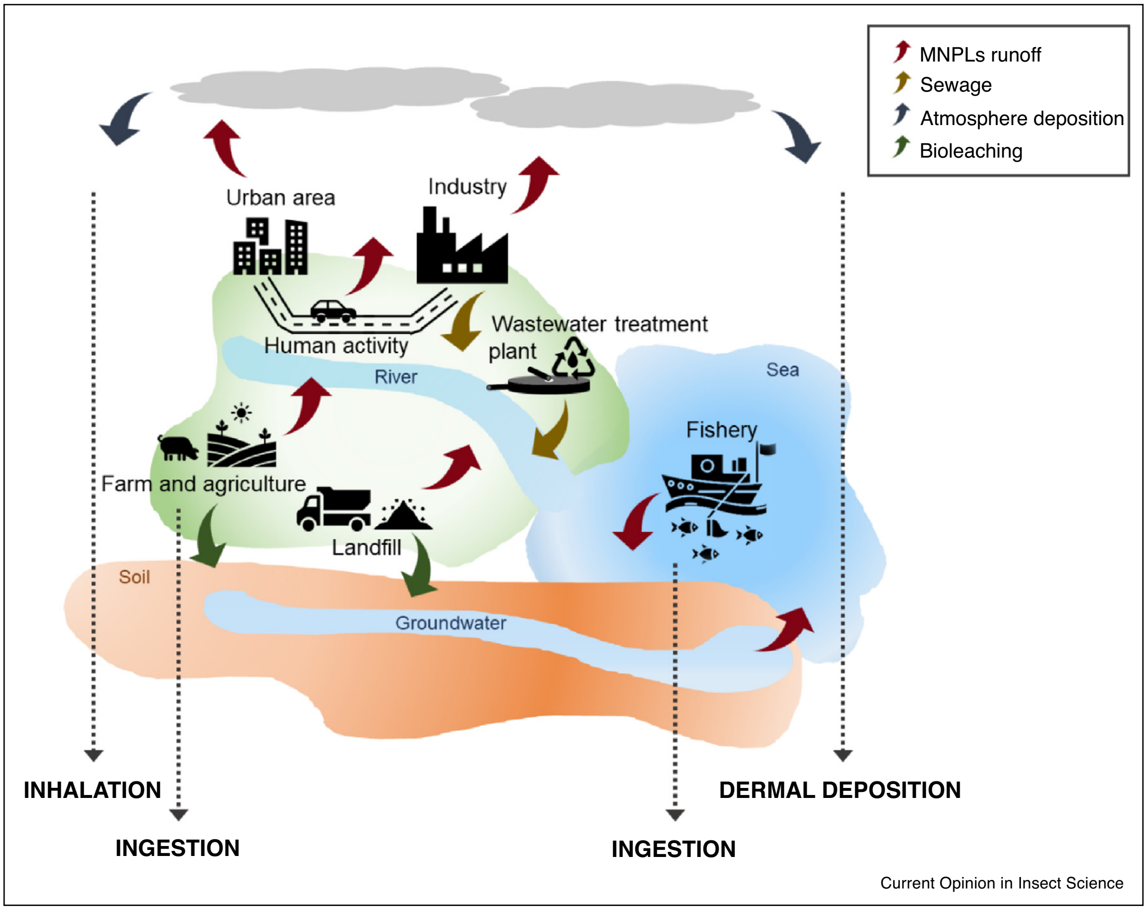
Human exposure to MNPLs

Wastewater treatment plants, large plastic fragmentation, solid waste management, aquaculture, runoff, agriculture, fishing, or industrial factories (among others) are sources of MNPLs pollution [15,22–24]. Low-density MNPLs often remain on the surface of seas, rivers, or oceans while high-density MNPLs tends to tend to sink and reach the deepest layers of the sediment [12,25]. MNPLs in aquatic environments can easily enter the food web by trophic transfer through seafood [13]. Besides, crops watered with contaminated water are another source of human exposure to MNPLs through ingestion. Agricultural activities use contaminated water to grow crops and plastics are continuously being degraded by microorganisms in the soils where crops are cultivated [9,22]. Moreover, agricultural products are the basis of the livestock farming diet. Thus, crops, food products derived from animals, and drinking water are sources of ingestion of MNPLs for humans. On the other hand, part of the MNPLs produced by the aforementioned sources remains resuspended in the air [17]. Accordingly, a continuous exchange of airborne pollutants takes place between atmospheric air and the ground by atmospheric deposition and release of MNPLs. Thus, a continuous fall of MNPLs occurs over the aquatic niches, soil, crops, and of course, human beings, leading to an increase in human exposure to plastic pollutants. Airborne MNPLs also entails a great exposure to MNPLs in humans through inhalation [26••]. As a summary, the MNPLs spread over the different environmental niches as indicated in Figure 1 through an interconnected network. Consequently, humans are exposed to plastic microparticles through different pathways.

Estimation of human global exposure to MNPLs

To estimate the total burden of exposure to MNPLs in humans we have carried out a systematic review of different studies published during the last three years.

Figure 1



Interconnection network through which MNPLs are distributed throughout all environmental niches, reaching humans through different exposure routes.

In cases that recent studies were not available, we selected studies previously published. Using PubMed, we have combined the following keywords: plastic particles, nanoplastic, microplastic, vegetables, fruit, seafood, fish, water, salt, sugar, beer, cereals, meat, milk, food, ingestion, inhalation, airborne, dermal contact, dermal deposition. The mean amount of MNPLs in each food group is indicated in Table 1, as well as the total amount of MNPLs ingested and inhaled. The values shown were obtained averaging over the different selected studies. Publications analyzed were selected following three main criteria: they include blanks, they include one or more methods to identify and verify MNPLs, and the number of particles/mass of items can be inferred from the reported results. Regarding the methods used to detect MNPLs, all the selected studies include microscopy inspection as a first approach to identify MNPLs. 87.87% of the total of analyzed publications verify the identity of the particles using spectroscopy-based methods. Thus: 63.63% of the studies use FTIR (Fourier Transform Infrared), 15.15% using Raman spectroscopy, and 9.09% using SEM (Scanning Electron Microscopy) coupled to EDX (Energy Dispersive X-Ray Spectroscopy). The identification of MNPLs in the rest of the studies (12.12%) is based on different microscopic techniques such as fluorescence microscopy, polarized light, or SEM.

Exposure to MNPLs via ingestion

The basic human diet includes fruits and vegetables, meat, fish, cereals and legumes, and water as the main hydration source.

The number of particles ingested with fruits and vegetable intake was recently determined by Oliveri Conti *et al.* [27•]. A mean amount of 132 740 p/g (particles/gram) MNPLs were determined in five frequently consumed fruits and vegetables (apples, pears, broccoli, lettuce, and carrots) supplied by different grocery shops. Taking these data as a representative for this food group, and following the WHO recommendation to include at least a daily

Table 1

Overall estimation of the total exposure to MNPLs in humans through different routes

Exposure-pathway	Product	Recommended-estimated consumption	Mean MNPLs	Daily intake of MNPLs	Annual intake of MNPLs	Total MNPLs/year
Ingestion	Fruit and vegetables	400 g/day	132 740 p/g	53.09×10^6	19.38×10^9	2.93×10^{10}
	Seafood	22.41 kg/year	0.98 p/g	60.38	22.04×10^3	
	Bottled water	2 L/day	13.55×10^6 p/L	27.10×10^6	9.89×10^9	
	Salt	5 g/day	142.80 p/kg	0.71	260.61	
	Alcohol	6.40 L/year	4.05 p/L	0.07	25.92	
Inhalation	Air	8.64 m^3/day	0.68 p/m^3	5.92	2.16×10^3	$2 .16 \times 10^3$

intake of 400 g of fruit and vegetables [28], humans would be ingesting 53.096×10^6 p/day.

For the estimation of MNPLs in seafood, meaning aquatic species fit for human consumption, only publications from the last three years including data corresponding to particles per gram of seafood were included (see Supplementary Table). Accordingly, a mean content of 0.98 p/g of seafood was determined. Assuming the annual global seafood consumption of 22.41 kg per capita [29], the global per capita MNPLs consumption linked to seafood is 22.04×10^3 p/year.

Regarding the MNPLs uptake via drinking water, it must be considered that the adequate water diary intake as reported by the EFSA [30] is 2 L for females and 2.5 L for males. Different authors have assessed the amount of MNPLs in bottled as well as in tap water, reporting high variability in the data. Thus, although Mason *et al.* [31] reported an average of 325 p/L in samples of plastic packaged water purchased globally, 2649 p/L were detected by Oßmann *et al.* [32], and only 3.57 p/L were found by Kosuth *et al.* [33•]. The aforementioned authors refer to these particles as anthropogenic debris and they do not completely ensure the origin of the particles due to the identification methods used. Conversely, Zuccarello *et al.* [34] reported an average of 54 200 000 p/L in the water contained in plastic bottles. Taking all these data, humans would ingest an average of 13 552 977.57 p/L of water packaged in single-use plastic bottles, which translates into 27 105 955.14 p/day assuming a total consumption of 2 L of bottled water per day. Nevertheless, the large variability of data makes to be very cautious about the validity of these data. The lack of powerful and standardized methods to identify/quantify MNPLs is alarming and huge efforts are required to fill this weakness [35].

Another common source of MNPL ingestion is table salt. Many authors have evaluated the microplastics content in different table salt samples from different countries and brands. High variability was reported in the different studies ranging from 9.77 p/kg [36] to 212 p/kg [33•] although the highest ratio was 506 p/kg found in samples analyzed by Kim *et al.* [37]. Averaging these data, we obtain an estimated amount of MNPLs in table salt of 142.8 p/kg. Since the WHO recommends a limit of salt intake of 5 g per day for healthy adults, humans would be ingesting 0.714 p/day with table salt consumption.

The only study determining nanoparticle contamination in sugar probably is that of Liebezeit *et al.* [38] in 2013, where authors determined 217 fibers/kg and 32 fragments/kg in sugar samples. Regarding WHO recommendation about sugar consumption that should not exert the limit of 27 g/capita/day [39], humans could be ingesting 2,138.53 fibers/year and 315.36 fragments/year. However, the authors do not mention whether these fragments were plastic' particles neither verify the identity. Besides, the methods used are outdated and there is no recent literature on this topic; so, numbers may be overestimated.

Regarding MNPLs intake via alcohol consumption, as reported by the WHO [40], the worldwide alcohol consumption per capita (15 years and older) was 6.4 L in 2016. Only a few studies regarding the presence of MNPLs in alcoholic beverages have been found, and all focused on the presence of MNPLs in beer. Nevertheless, most of them are not recent studies, the methods used to confirm MNPLs presence as well as the inclusion of blanks are lacking, or have discredited the results [41]. The most recent study was the one published in 2018 by Kosuth *et al.* [33•], where the authors determined an overall mean of 4.05 p/L in different beer samples. Assuming these particles as MNPLs and an alcohol consumption comprised entirely of beer, MNPLs uptake linked to alcohol consumption would be 25.92 p/year.

No data on the presence of MNPLs in cereals has been found. Nevertheless, García-Ibarra *et al.* [42] studied the contamination of cereals and cereals-based foods by chemical migrants from plastic packaging. Although the presence of MNPL in cereals was not analyzed in this study, it can be concluded that there is a constant degradation of packaging and release of contaminants to the content. Besides, irrigation of cereal crops with waters containing MNPLs may also contribute to food contamination.

Similarly, contaminants migrating from plastic packaging in beef pieces were identified [43]. In the same way that these contaminants can come off from the packaging and migrate to the food, MNPLs break off can contaminate packaged meat food. Moreover, it has been reported that ruminants accumulate indigestible plastic materials in the rumen. Thus, MNPLs and other contaminants can enter the human food chain through milk and meat contaminated products [44]. Unfortunately, there is a lack of data quantifying MNPLs in, plastic-packaged or not, meat, milk, cereals, and many other food products. However, knowing that 6.4, 11.1, 14.7, and 1.8 kg/capita of beef and veal, pork, poultry meat, and sheep meat, respectively, were consumed all over the world during 2019 [45], and taking into account the lack of data regarding MNPLs content in the many other food groups, the amount of MNPLs ingested by humans is underestimated.

Exposure to MNPLs via inhalation

Although inhalation is a well-known pathway of exposure to MNPLs in humans, few studies have addressed this concern. From those studies analyzed [46–48], we estimated an airborne MNPLs concentration of 0.685 p/m^3. Considering a respiration frequency of 12 breaths/min and a tidal volume of 0.5 L, the breathing rate is 8.64 m^3/day; so, humans would inhale 5.918 p/day. However, airborne MNPLs estimation depends on the sampling methodologies, air renovation rates, and other factors such as human activity, furniture, or cleaning habits. Moreover, considering the COVID-19 pandemic, we assume inhalation of MNPLs is underestimated since the use of masks for long periods has become common all over the world.

Exposure to MNPLs via dermal contact

Few are the studies regarding MNPLs fallout in different geographic locations and environments (indoor/outdoor, urban/suburban/remote) [17,49••,50]. The variability of the conditions analyzed in those studies and the results make it difficult to establish comparisons between them. Thus, the deposition ratio fluctuates in a wide range between 36 and 1008 p/m^2/day, with a mean value of 366.87 p/m^2/day. Regarding deposition rate values, and considering the continuous shedding of fibers from clothing [51,52], dermal contact with MNPLs is evident. Even so, no studies are quantifying dermal exposure to MNPLs and its potential effects at this point.

Conclusion

Plastics, and specifically MNPLs, are gaining attention as potential human health risk factors; but the studies found in this regard are very limited. It is specifically notable for the lack of human biomonitoring studies evaluating the health impact of MNPLs. This is caused, basically, by the difficulty of detecting, characterizing, and analyzing MNPLs in human samples due to the lack of guidelines or standardized protocols allowing the homogenization and harmonization of the results obtained by different authors [53]. This makes data comparison very difficult. Although the greatest exposure to MNPLs in humans occurs through inhalation and ingestion, other exposure pathways such as dermal contact cannot be underestimated. However, the lack of studies about this stands out. Moreover, all exposure quantification studies are carried out in a specific context, by analyzing an exposure route in a given environment. This makes it difficult to estimate the overall total exposure to humans anywhere in the world. In addition, it must be remembered that the MNPLs ability to cross the different epithelial barriers and, consequently, their distribution in the different organs and tissues, can determine the associated risk of these exposures. As it has been previously indicated, the lack of human biomonitoring studies is a great gap limiting the determination of both the real intake of MNPLs and its potentially harmful effects. At this point, it should be indicated that using *in vitro* models of the human intestinal barrier, an important uptake of nanopolystyrene (as a model of MNPLs) was observed, translocating through the barrier [54•]. In this review microplastics are considered as a whole without differentiation between chemical composition, morphology, and size; but their potential health impact in humans can be strongly influenced but such characteristics. The chemical nature of microplastics reflects those of macroplastic from which they come. Thus, the chemical nature of those microplastic most often detected in water and soil are polyethylene, polyethylene terephthalate, propylene, styrene, polyvinyl chloride, nylon, and polyamides [55••]. In the same way, the morphologies they show are granules, fragments, microbeads, fibers, and foams. All this reflects the complexity of microplastics exposures and, consequently, the difficulties of establishing sound associations between exposures and effects.

Here, we estimated that the total burden of human exposure to MNPLs is 2.93×10^{10} p/year, from recent data available. Nevertheless, it should be remembered that these values must be taken with caution due to the lack of strongly established methodologies for their detection. Even so, this estimation would vary if urbanization, religious beliefs or ethical concerns, social or cultural norms, gender, age, and health concerns among other factors, were considered.

So, we consider that the priority concern is to establish and validate guidelines and methods to detect and quantify MNPLs in environmental and food samples, as well as in biological matrices. With this, reported studies would be more homogeneous and comparable regarding the methodology used and the data reported. Besides, reliable quantification of MNPLs in different types of samples would allow having a reliable reference of the real exposure of humans to MNPLs. Furthermore, *in vivo* and *in vitro* studies with more realistic concentrations of MNPLs would be carried out to elucidate the toxic effects of the aforementioned exposure in different model systems. Given this information, the following steps should be to carry out biomonitoring studies in humans what would allow to accurately establish the exposure levels and the induced effects of MNPLs. Even so, some studies are reporting the toxic effects of MNPLs both in *in vivo* and *in vitro* systems, as well as the ability of MNPLs to cross biological barriers [54•,56,57]. From these data, it could be hypothesized that MNPLs can reach the circulatory system affecting the immune system cells, and be distributed throughout the human body, even reaching different organs. Although the specific effects at short and long-term, and the bioaccumulation of MNPLs in each organ, should be deeply studied to get conclusions, data suggests that MNPLs are easily internalized by human cell models and altering their functionality. Moreover, they can disturb the microbiota affecting homeostasis and triggering toxic effects in the metabolism of mammalian models [54•,56–58].

Finally, and to highlight the increasing relevance of this topic, it must be indicating that inside the EU Horizont-2020 program, a specific call on '*Microplastics and nanoplastics in our environment: Understanding exposures and impacts on human health SC1-BHC-36-2020)*' was launched. The five recently funded projects in this call have been organized as a cluster, and the research will start in April 2021. It is expected that most of the questions asked can be solved during the development of such projects.

Author contribution

JD and RM have collaborated in all the stages of this revision work.

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Conflict of interest statement

Nothing declared.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.cofs.2021.01.004.

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