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Review article

# From oceans to dinner plates: The impact of microplastics on human health

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A B S T R A C T

Microplastics, measuring less than 5 mm in diameter, are now found in various environmental media, including soil, water, and air, and have infiltrated the food chain, ultimately becoming a part of the human diet. This study offers a comprehensive examination of the intricate nexus between microplastics and human health, thereby contributing to the existing knowledge on the subject. Sources of microplastics, including microfibers from textiles, personal care products, and wastewater treatment plants, among others, were assessed. The study meticulously examined the diverse routes of microplastic exposure—ingestion, inhalation, and dermal contact—offering insights into the associated health risks. Notably, ingestion of microplastics has been linked to gastrointestinal disturbances, endocrine disruption, and the potential transmission of pathogenic bacteria. Inhalation of airborne microplastics emerges as a critical concern, with possible implications for respiratory and cardiovascular health. Dermal contact, although less explored, raises the prospect of skin irritation and allergic reactions. The impacts of COVID-19 on microplastic pollution were also highlighted. Throughout the manuscript, the need for a deeper mechanistic understanding of microplastic interactions with human systems is emphasized, underscoring the urgency for further research and public awareness.

## 1. Introduction

Plastics are widely used in contemporary society, with an estimated 320 million tons manufactured annually across the globe [1]. However, the durability and persistence of plastic materials have resulted in significant environmental problems, including the

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**Abbreviations**

| | |
|---|---|
| CP | Cellophane |
| EPS | Expanded polystyrene |
| LDPE | Low-density polyethylene |
| HDPE | High-density polyethylene |
| MP | Microplastic |
| PA | Polyamide |
| PB | Poly(1-butene) |
| PE | polyethylene |
| PES | Polyester |
| PET | Polyethylene terephthalate |
| PP | Polypropylene |
| PPE | Personal protective equipment |
| PS | Polystyrene |
| PU | Polyurethane |
| PVA | Polyvinyl acetate |
| PVC | Polyvinyl chloride |
| WWTP | Wastewater treatment plant |

accumulation of plastic waste in landfills, waterways, and oceans. Approximately 8 million tons of plastic waste enter the ocean annually [2]. After being introduced to the water environment, plastic can undergo degradation caused by factors like microbiological activity, radiation, and mechanical stress, leading to the disintegration and fragmentation of larger plastic items into smaller particles called microplastics [3,4]. Due to their potential effects on both human health and the environment, microplastics are an especially dangerous type of plastic pollution.

Microplastics are small plastic particles, typically measuring less than 5 mm in diameter. Microplastics can arise from diverse origins, encompassing the breaking down of larger plastic products [5,6], the release of microfibers from textiles during laundering [7], and the inclusion of microbeads in personal care products [8]. Additionally, the degradation of larger plastic particles in the environment can contribute to the formation of microplastics, as they progressively break down into smaller fragments [9,10]. The extensive utilization of plastic goods has resulted in the ubiquity of microplastics in various environmental mediums, such as soil [11], water [12], and air [13]. Previously seen as a danger solely to marine organisms, microplastics have gradually and inevitably infiltrated the food chain, becoming a part of the human diet. As a result, growing concern exists regarding the potential impacts of microplastics on human well-being. Recently, investigations have shown evidence of microplastics in human stool [14,15], saliva [16], and even placenta [1], raising fears of potential bioaccumulation and adverse health effects. While the mechanisms by which microplastics may impact human health are still being investigated, there is evidence that they are capable of entering the body by ingestion, inhalation, and dermal contact.

The ingestion of microplastics is a prevalent route of exposure, with microplastics being detected in various food and beverage items such as seafood, drinking water, and beer [17,18]. Inhalation of microplastics may occur through the air, particularly in indoor environments with high levels of dust [19], while dermal contact with microplastics can happen while using personal care products or coming into contact with contaminated surfaces [20].

Although the precise health consequences of microplastics on humans are still not entirely comprehended, results from studies show that microplastics could present various potential health hazards. These risks encompass inflammation, oxidative stress, and tissue damage [21,22]. Specifically, there have been reports linking microplastic exposure to adverse effects on male fertility and sperm quality, potentially posing a threat to successful conception [23]. Some studies have also suggested that microplastics may potentially build up in the body over time and have long-term negative effects on health [24,25]. For instance, microplastics can cause inflammation in the body, which can lead to a number of other health problems, such as heart disease [26], cancer [27], and autoimmune disorders [28]. Additionally, microplastics can generate oxidative stress, which is a condition that can damage cells and DNA. This can lead to a number of health problems, including neurodegenerative diseases and reproductive problems [29,30]. These health effects are typically exacerbated by the chemical additives, such as polychlorinated biphenyls and phthalate esters, added to microplastics during production. Microplastics are therefore recognized as an emerging environmental and public health concerns with the potential to affect both human well-being and the natural environment.

As research on the health impacts of microplastics continues to develop, it is important to constantly address the sources of these tiny particles and highlight their potential impacts on human health. Hence, the objectives of this review are to investigate and elucidate the multifaceted relationship between microplastics and human health, shedding light on the potential risks posed by these ubiquitous pollutants. The study encompasses an extensive examination of microplastic sources, routes of exposure, and their various modes of interaction with the human body. Through rigorous analysis, the study seeks to identify the pathways through which microplastics infiltrate human systems, including ingestion, inhalation, and dermal contact, thereby establishing a comprehensive understanding of potential health implications. The study is divided into three major sections: (a) sources, (b) routes of exposure, and (c) health impacts of microplastics on human health. This study contributes to the current pool of knowledge regarding the health effects of microplastic exposure.

## 2. Classifications of microplastics: primary and secondary microplastics

Microplastics can exist in different forms, and their characteristics can vary depending on their source and environmental conditions. Table 1 provides an overview of the various forms of microplastics and their corresponding physical features. Microplastic fragments typically range in size from a few micrometers (μm) to a few millimeters (mm). Pellets are often uniform in size and typically range from about 1 mm to a few mm in diameter, while fibers are usually longer and narrower compared to other microplastic types, ranging from around 10 μm to a few mm in length. Their diameter can vary widely, from less than 1 μm to several micrometers [31].

### 2.1. Primary microplastics

Primary microplastics refer to tiny plastic particle that are intentionally produced in their micro-sized form or are generated as a by-product during manufacturing processes [33]. These microplastics are purposely produced with a particular purpose in mind, such as serving as powders for injection molding, abrasive particles, or resin pellets for the efficient movement of polymers between different manufacturing locations [34,35]. Additionally, they can stem from the wearing down of large plastic objects during their production, usage, or servicing, such as the worn out of tires while driving or the wearing away of synthetic fabrics during washing [36]. In general, the particles can take various forms, including microbeads, microfibers, and resin pellets.

Microbeads are tiny plastic spheres typically used in personal care and cosmetic products, such as exfoliating scrubs and toothpaste. These microplastics are primarily intended to serve as texture-enhancing agents or abrasives. However, their small size makes them prone to entering water systems, and they often prove challenging to successfully filter out through wastewater treatment plants [37, 38]. Microfibers, on the other hand, are thin strands of plastic that come from textiles like synthetic clothing, carpeting, and upholstery. Approximately 70 million tons of fiber are manufactured each year by the clothing and fashion sectors, and laundering constitutes a substantial amount of microfiber pollution observed in waterways [39]. Microplastics are released by textiles at various stages of their life cycles, including during production, usage, washing, and even after disposal [40]. Furthermore, microfibers have been detected in diverse sources such as cigarette filters, carpets, and personal care items like face masks and wet wipes [40,41]. Resin pellets, also known as nurdles or nibs, are the raw materials used in the production of plastic products [42]. These small plastic pellets are transported and processed to create a wide range of plastic products. However, mishandling or unintentional spillage of these pellets during production, transport, or manufacturing can result in their release into the environment, endangering aquatic environments [36].

The presence of primary microplastics in the environment has garnered significant attention due to their widespread distribution and potential adverse impacts on marine life, and consequently, on human well-being. Microplastics can be mistakenly consumed by marine organisms, which can have detrimental consequences for their well-being and survival [43]. Furthermore, primary microplastics possess the ability to adsorb and transport harmful chemicals, thereby intensifying the ecological hazards they present.

Furthermore, primary microplastics can also disperse from sources such as the coating and pre-treatment of marine vessels, road markings [36], the wearing down of synthetic cooking utensils, and the soles of footwear, among various others [44].

### 2.2. Secondary microplastics

Secondary microplastics encompass tiny plastic particles that arise from the deterioration and fragmentation of larger plastic items like bottles, bags, and packaging materials. Unlike primary microplastics, which are purposefully created in their micro-sized form, secondary microplastics emerge as a consequence of the gradual weathering, breakdown, and disintegration of larger plastic objects [45,46]. Factors contributing to the degradation of plastic items include mechanical forces (such as waves and abrasion), chemical reactions, and exposure to sunlight (UV radiation). These processes gradually break down the plastic into smaller and smaller fragments, ultimately forming secondary microplastics [47]. The prevailing belief is that the predominant proportion of microplastics in the environment consists of secondary microplastics because of how frequently macroplastics are released into the environment [48].

Secondary microplastics can take different forms, including fragments, fibers, and microbeads (Table 1). Plastic fragments are irregularly shaped pieces that emerge from the disintegration of larger plastic objects [32]. Fibers are thin strands that come from textiles such as clothing, ropes, and fishing nets. Microbeads, similar to those in primary microplastics, are tiny spherical particles. Once released into the environment, secondary microplastics can contaminate ecosystems, including water bodies, soil, and air. They

**Table 1**
Classification and physical attributes of microplastics. Adapted from Ref. [32].

| Microplastic category | Physical characteristics |
|---|---|
| Fragments | Uneven form, sharp, thick, charred edge |
| Granules | Typically circular in form |
| Filaments | Extremely small, short, and sometimes long |
| Pellets | Usually flat on one side, but with a round appearance. |
| Films | Supple and thin |
| Foams | Soft, yellow to white in color |
| Fibers | Circular shape, the length is significantly greater than the flexible, thin breadth. |

can be transported by wind, water currents, or human activities, spreading their presence to remote areas [49].

These tiny fragments of microplastics present notable dangers to both the environment and organisms. Marine life, in particular, is exceptionally susceptible to their detrimental effects. Marine animals may unknowingly consume microplastics, which can result in ingestion-related problems and digestive complications [50]. Moreover, the occurrence of secondary microplastics in aquatic settings can disrupt marine habitats and ecosystems, thereby influencing the overall well-being and equilibrium of marine organisms. The various forms of primary and secondary microplastics are shown in Fig. 1.

## 3. Sources of microplastics

There are numerous sources of microplastics. Through the usage of personal care products with microbeads and the laundering of textiles, which sheds microfibers, they may be discharged into the environment. Microplastics may also develop as a result of the breakdown of bigger plastic particles in the environment. Over time, these larger plastic particles may degrade ever-tinier fragments. Depending on the size, the microplastic produced when bigger plastics break down can take on many shapes and forms.

### 3.1. *Microfibers from textiles*

Microfibers from textiles are a significant source of microplastic pollution. They are typically composed of polyester and nylon and can be found in a range of clothing items, including athletic wear, fleece, and other synthetic materials [51,52]. When these synthetic textiles are laundered, they shed small fibers that can bypass wastewater treatment plants and ultimately find their way into the environment [53]. Synthetic textile fibres released during cloth washing is a great contributor of MPs found in the ocean. Microplastic pollution from synthetic clothes occurs when they are washed, as the mechanical and chemical stresses during laundering release tiny microfibers [54]. These microfibers are too small to be filtered by wastewater treatment plants, ultimately ending up in the oceans and seas [55,56]. Up to 1900–1,000,000 fibers are released when washing a single garment, over 6,000,000 fibers when washing polyester fabrics, and 700,000 fibers in acrylic fabrics [57]. De Falco et al. [58] investigated how washing synthetic clothes contributes to microplastic pollution. Real-scale washing experiments using a household machine were conducted to examine microfiber release and textile influences. Wastewater samples were collected and filtered, revealing microfiber releases ranging from 124 to 308 mg per kg of fabric, amounting to 640,000 to 1,500,000 microfibers. Textile characteristics, such as fiber composition and twist, affected the release. Clothes made with a polyester/cellulose blend shed a significant amount of cellulosic microfibers. Filters with pores of 60 μm or larger were able to capture the bulk of these shed microfibers, which are detrimental to marine life.

### 3.2. *Personal care products*

In personal care products, primary microplastics are more prevalent and can be found in various forms, including microbeads, microfibers, and microcapsules. Personal care products encompasses a range of products designed to maintain personal cleanliness, enhance appearance, and promote well-being. These products often include items such as soaps, shampoos, conditioners, body lotions, deodorants, and cosmetics. They may also cover skincare products like moisturizers, serums, and sunscreens. When these products are used and washed off, the microbeads can enter the environment through wastewater and can potentially be ingested by marine

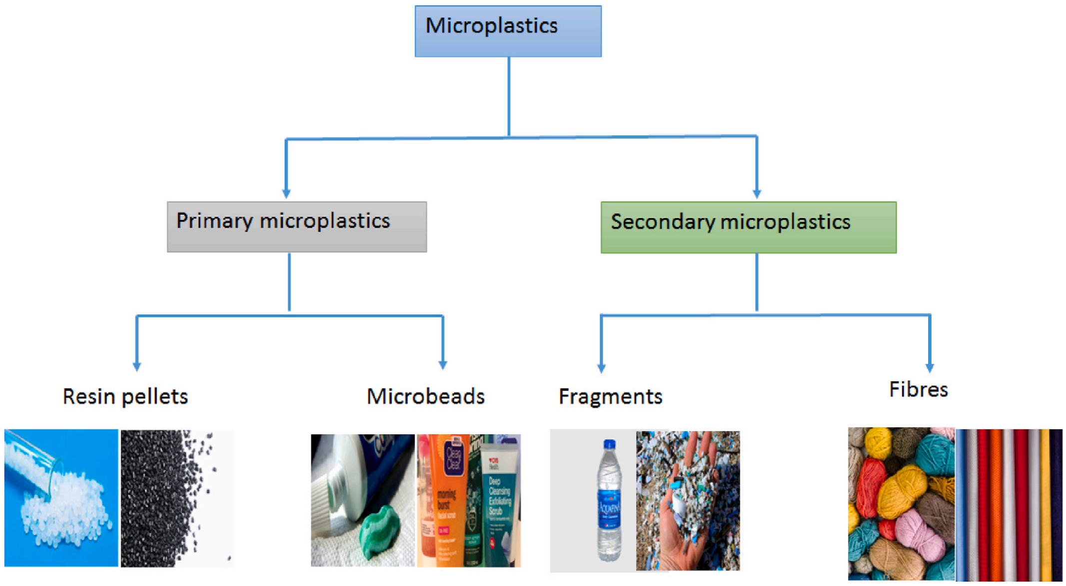


**Fig. 1.** Primary and secondary forms of microplastics.

organisms and other wildlife [59,60]. Cosmetic products typically contain microbeads ranging from 0.5% to 5% of their composition, with an average size of 250 μm. For instance, toothpaste alone releases approximately 4000 microbeads per single use [57]. The majority of these microbeads, along with fibers, are small enough to bypass wastewater treatment plants and are not captured by the facility. As a result, they ultimately find their way into water systems [61].

In recent times, there has been significant public interest in microplastic particles originating from personal care products. Consequently, there is a particular emphasis on understanding the extent to which microplastics from personal care products contribute to the overall environmental microplastic pollution [62]. A research conducted in Macao, China, a densely populated city, revealed that the utilization of personal care products within the region could result in the release of more than 37 billion microbeads annually into the environment [63]. Lei et al. [64] examined the presence of microplastics in personal care and cosmetic products and their effects on the aquatic environment. Through a survey conducted in multiple supermarkets in Beijing, China, it was discovered that 7.1% of facial cleansers and 2.2% of shower gels contained microplastics. The predominant material of these microplastics was identified as polyethylene. The study further estimated that approximately 39 tons of microplastics are discharged into the environment from shower gels in China. Further, Praveena et al. [65] studied the presence of microplastics in personal care products like facial cleansers and toothpaste in Malaysia. Through a survey involving 214 participants, microplastics were detected in these products. The facial cleansers contained plastic polymers like LDPE and polypropylene, while toothpaste contained LDPE. The study projected an annual release of approximately 0.199 trillion microplastics into Malaysia's marine environment due to these products.

### 3.3. Wastewater treatment plant

The treatment of wastewater is commonly conducted to eliminate organic substances and nutrients prior to release. Nevertheless, this procedure is generally ineffective in eliminating additional pollutants like microplastics, which have the potential to be discharged into aquatic ecosystems, potentially causing harmful consequences for aquatic organisms [66]. Wastewater treatment plants (WWTPs) are intended to function as a method of reducing organic materials, nutrients, and various pollutants, including microplastics, present in wastewater. Consequently, these treatment plants can inadvertently become a reservoir for microplastics. The wastewater originating from WWTPs infiltrates aquatic ecosystems through the release of effluents, sewage overflow during periods of heavy rainfall, and runoff resulting from the application of sewage-based fertilizers [67]. In essence, WWTPs are the entry point for textile microfibers and personal care product microbeads into the marine environment. According to reports, the WWTP situated along the River Clyde in Glasgow discharges approximately 65 million microplastic particles into the surrounding water every day [68]. Kazour et al. [69] investigated the origins of microplastic pollution in saltwater environments, with particular emphasis on discharges from wastewater treatment plants and an abandoned coastal landfill. The researchers analyzed microplastics in various samples and found that the investigated WWTP discharged an estimated 227 million microplastics per day, primarily consisting of fibers and fragments. Microplastics were detected in all examined matrices, with higher concentrations near the coastal landfill. Also, Gündoğdu et al. [70]

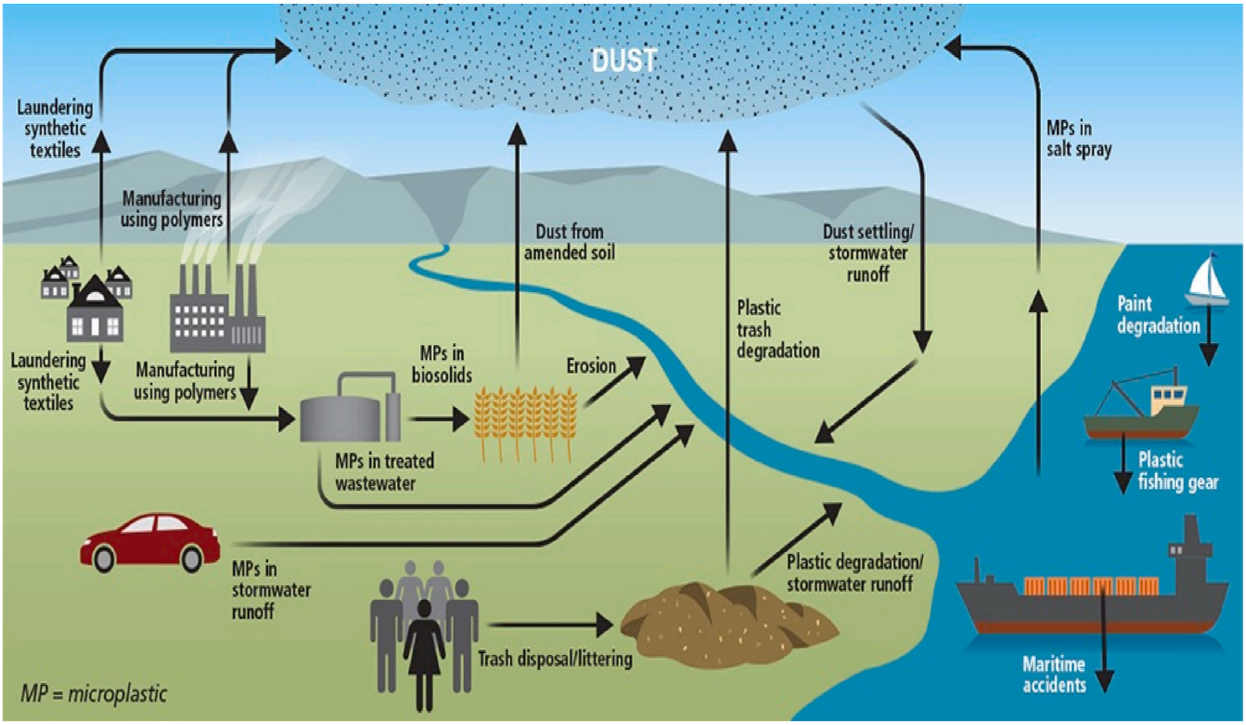


**Fig. 2.** Various pathways through which plastics and microplastics enter and circulate within terrestrial and marine ecosystems [77].

examined two wastewater treatment plants in Turkey to assess microplastic concentrations. The influent water had 1 million to 6.5 million particles per day, while the effluent water contained 220,000 to 1.5 million particles per day. The study identified a total of seven distinct polymer types, with polyester being the most commonly observed.

### 3.4. Biosolids and other sources

Biosolids, which are the treated water sludge generated from wastewater treatment, significantly contribute to plastic pollution in terrestrial environments. They are commonly utilized as fertilizers in agricultural land to recycle organic matter, provide nutrients, and improve soil quality for cultivation [71,72]. This practice results in a considerable deposition of microplastics onto farmlands. In Europe, an estimated 63,000 to 430,000 tons of microplastics are deposited annually, while in North America, the range is 44,000 to 300,000 tons [73]. Consequently, agricultural soils serve as extensive reservoirs of microplastics, and these particles are further transported to the aquatic environment through various means such as rainfall, leaching, and irrigation [74].

Additionally, plastics find their way into the ocean through the accidental loss or deliberate dumping of fishing equipment utilized in fishing activities [75]. Over time, these materials undergo degradation due to sunlight exposure, breaking down into various fragments of microplastics. Recreational activities taking place on beaches significantly contribute to the contamination of coastal waters, serving as pathways for transporting MPs into the oceans. In fact, beach litter alone accounts for approximately 80% of the plastic debris found in the ocean [75]. Anthropogenic waste, including plastic particles, was identified as a significant component of flotsam in the German Bight of the North Sea, comprising more than 70% (32.4 particles/$km^2$) of the floating debris present in the sea [76]. Activities such as unregulated fishing, recreational pursuits, and maritime operations, coupled with population shifts favoring coastal areas, will inevitably contribute to a greater influx of plastic waste into the ocean in the future [75]. Fig. 2 depicts the sources, transport, and disposition of microplastics in the terrestrial and marine environments.

## 4. The far-reaching impact of COVID-19 on microplastic pollution

The COVID-19 pandemic, caused by the novel coronavirus SARS-CoV-2, has undeniably transformed the global landscape in myriad ways. Beyond its direct health implications, the pandemic has exerted significant indirect effects on various environmental aspects, including microplastic pollution. At the outset of the pandemic, disruptions in global supply chains and manufacturing industries led to shifts in plastic production and consumption. The surge in demand for personal protective equipment (PPE) such as masks, gloves, and face shields, along with increased usage of single-use plastic items (e.g., packaging for takeout food and online deliveries), contributed to a spike in plastic production [78–80]. During the pandemic, approximately 65 billion gloves and 129 billion face masks were utilized on a global scale each month [81]. At present, the outbreak has led to a daily global production of around 1.6 million tons of plastic waste, accompanied by the disposal of 3.4 billion single-use face masks every day [82]. This abrupt alteration in plastic consumption patterns exacerbated microplastic pollution, as many of these items degrade over time into smaller particles.

Also, lockdowns, restrictions on movement, and concerns about viral transmission prompted changes in waste management systems globally. Reduced recycling capacity, closure of recycling facilities, and delays in waste collection led to improper disposal of plastic waste [83]. As a consequence, more plastic waste entered the environment, ultimately contributing to the breakdown of larger plastic items into microplastics. The inadequate management of plastic waste during the pandemic amplifies the existing microplastic pollution problem. Since the start of the pandemic, there has been a rise of 1.6 million metric tons in worldwide plastic waste [84]. Recently, Shukla et al. [85] explored the ecological consequences of increased plastic use during the COVID-19 pandemic, particularly face masks. It was found that over 1.5 million tons of face masks are used yearly, leading to about 4.2 million tons of plastic waste and 9774 thousand tons of microplastics across 36 countries. This undermines global plastic reduction efforts, highlighting the urgency of addressing these risks from heightened plastic dependence amid the pandemic. Akhbarizadeh et al. [86] examined PPE waste on Bushehr port's Persian Gulf coast during Covid-19. About 2380 PPE items were gathered from nine locations, evaluating their role in microplastics. Beaches showed no notable distinctions, with an estimated disposal of 350 items daily and 127,750 yearly. Over 10% of collected PPE deteriorated, notably surgical masks and torn gloves, adding to microplastics in oceans.

While the pandemic initially diverted attention and resources away from environmental issues, it also spurred novel insights and responses to microplastic pollution. Researchers recognized the interconnectedness of public health and environmental well-being. The pandemic highlighted the necessity of resilient waste management systems and sustainable consumption practices to mitigate future disruptions. As a result, there has been renewed interest in addressing microplastic pollution through policy initiatives, technological advancements, and scientific research.

## 5. Routes of exposure to microplastics

Microplastic exposure can transpire through multiple pathways, encompassing ingestion, inhalation, and dermal contact. Various consumer products that originate from the sea, including salt and fish, can be impacted by marine pollution. This contamination can introduce microplastics into human bodies through the consumption of these products.

### 5.1. Ingestion

Ingestion of microplastics occurs when small particles of plastic are consumed through food or water. These particles can be found in seafood, bottled water, and other food products that have been contaminated with microplastics.

#### 5.1.1. Seafood

Seafood particularly shellfish, can contain microplastics due to their filter-feeding behavior. As microplastics are present in the water column, they can accumulate in the tissues of these organisms and be consumed by humans who eat them. Plastic consumption is observed across a range of organisms at various trophic levels within the food chain, including marine mammals, fish, invertebrates, and birds that consume fish [87]. Over 800 animal species have been documented as being exposed to plastic through ingestion or becoming entangled in it [88]. The small size of microplastics makes them readily ingestible by organisms with diverse feeding mechanisms, including those that feed on organic matter, those that feed on sediment, and those that filter feed [61,89]. The ingestion of microplastics has been documented in both natural environments and controlled laboratory studies involving a diverse array of marine organisms, including zooplankton [90,91], fish [92,93], seabirds [94], crustaceans [95], and bivalves [96], among others, which are meant for human consumption.

For instance, Li et al. [97] discovered that microplastics were detected in all commercially harvested bivalves sampled from a Chinese fishery market. The study identified a range of microplastic types, such as fibers, fragments, and pellets, in the examined bivalves. The most prevalent size class of microplastics was below 250 μm, constituting a significant proportion (33–84%) of the total microplastics found. These findings raised concerns about possible threats to human health linked to the consumption of seafood contaminated with microplastics. A study conducted by Rochman et al. [98] in Makassar, Indonesia, and California, USA, confirmed the presence of microplastic debris in fish and shellfish meant for human consumption. According to the study, plastic debris was prevalent in 28% of individual fish and 55% of species in Indonesia. In comparison, it was discovered in 25% of individual fish and 67% of species in the USA. Furthermore, microplastics were found in 33% of individual mussels, raising further concerns about possible health consequences from seafood consumption. In addition, Ghosh et al. [99] examined the presence of microplastics in fish from the Bay of Bengal, Bangladesh. Microplastics were found in all species, averaging 2.2 per fish, mostly as green fibers and films under 500 μm, primarily composed of polyethylene and polypropylene. Table 2 provides a more extensive overview of the global presence of microplastics in seafood.

#### 5.1.2. Bottled water

Microplastics have been detected in several brands of plastic bottled water. It is believed that the microplastics originate from the plastic bottles themselves, as well as from the bottling and shipping process. Although drinking-water treatment is generally effective in removing various waterborne particles, including microplastics, it is important to consider that certain components and distribution networks within treatment plants are made of plastic [105]. Over time, the erosion or degradation of these plastic materials can potentially introduce microplastics into drinking water [106]. In addition, the bottles and caps used for some bottled waters are also made of plastic, posing a potential source of microplastic contamination in drinking water [106,107]. In addition to bottled water, various water sources, including tap water, significantly contribute to the intake of microplastics in humans. On average, individuals are estimated to consume approximately 39,000 to 52,000 microplastic particles each year, with tap water accounting for approximately 3000 to 4000 MPs (equivalent to an average of 4.34 MPs per liter) of their total intake [108].

Mason et al. [109] examined microplastic contamination in bottled water from eleven brands purchased in nine countries. 93% of the 259 bottles that were tested had contamination. After background contamination was taken into consideration, an average of 10.4 microplastic particles >100 μm per liter of water, largely in the form of pieces and fibers, was discovered. Polypropylene was the most common polymer (54%). Additionally, smaller particles measuring between 6.5 and 100 μm increased the average count to 325 particles per liter, with the observed range spanning from 0 to over 10,000 particles. The study raises the need for more investigation into the health effects of microplastics in bottled water by arguing that the contamination may be caused by the bottling or packaging processes. Similarly, Schymanski et al. [110] investigated the microplastic concentration in water from various kinds of bottles obtained in Germany. Microplastic fragments were found in all samples, with nearly 80% of particles ranging from 5 to 20 mm, previously undetectable. Returnable plastic bottles had the highest average microplastic content (118 particles/L), followed by single-use plastic bottles (14 particles/L) and beverage cartons (11 particles/L). Polyester (PET) and polypropylene (PP) were prevalent in returnable bottles, while other plastics like polyethylene were found in beverage cartons and glass bottles. In the research conducted by

**Table 2**
Microplastic contamination in seafood.

| Location | Seafood | Polymer type | Dominant particle shape | Size | Level of MPs | Ref. |
|---|---|---|---|---|---|---|
| China | Commercial bivalves | – | Fibres, fragments, pellets | >250 μm | 2.1–10.5 items/g | [97] |
| North seas, Germany | *Mytilus edulis* | – | Fibres omitted | 5–10 μm | 0.36 item/g | [100] |
| Atlantic ocean, Germany | *Crassostrea gigas* | – | Fibres omitted | 16–20 μm | 0.47 iem/g | [100] |
| Pearl River estuary, China | Oysters | PE, PET, PP, PS, PVC, PA, CP, EPS | Fibres, fragments, pellets, sheets | 20–5000 μm | 1.5–7.2 items/g | [101] |
| French, Belgium, and Dutch North Sea | *Mytilus edulis* | PS, LDPE, HDPE | Fibres omitted | 15–1000 μm | 0.1–0.2 | [102] |
| English channel, UK | Pelagic and demersal fish | Rayon, PA, PES | Fibres, fragments, beads | 0.13–14.3 mm | 1.90 particles/fish | [103] |
| Bay of Bengal, Bangladesh | Commercial fish | PE, PP, PES, PU | Fibres, films, fragments, foams, granules | <500 μm | 2.2 MPs/individual | [99] |
| South eastern Arabian Sea, India | Commercial fish | PP, PE | Fragments, films, filaments, pellets, foams | 0.27–3.2 mm | 0.004–11.58 g/fish | [104] |

Oβmann et al. [107], it was discovered that microplastics were detected in all examined types of bottled mineral water. The quantities observed varied, with the range being from 2649 ± 2857 particles per liter in single-use PET bottles to 6292 ± 10521 particles per liter in glass bottles. Table 3 provides a concise overview of the documented microplastics discovered in plastic bottled water.

### 5.1.3. Other food products

Microplastics have been detected in various food products, such as honey, milk, beer, and salt. These products may become contaminated with microplastics during processing or packaging. Liebezeit and Liebezeit [113] found microplastic contamination in all 24 analyzed German beer brands, with fiber counts ranging from 2 to 79 fibers/L, fragment counts ranging from 12 to 109 fragments/L, and granule counts ranging from 2 to 66 granules/L. In another study, honey samples from different European countries were analyzed and found colored fibers in all of them, with counts ranging from 40 to 660 fibers/kg of honey [114]. Fragments were also present but less abundant, ranging from 0 to 38 fragments per kg of honey. The colored material was believed to originate from environmental sources introduced during honey processing or bee transport. Li et al. [115] found microplastics in widely consumed beverages around the world, including beers with 20–80 $mL^{-1}$, bottled mineral water with 10 $mL^{-1}$, and tea leaves with 200–500 $g^{-1}$ contamination levels. Various microplastic shapes were identified, including quasi-spherical particles, fragments, and fibers. Sources of contamination was attributed to raw materials, atmosphere, and tools/containers, raising concerns about heavy metals and antibiotics accumulation.

Iñiguez et al. [116] analyzed some commercial table salt samples from Spain, with the results revealing microplastic concentrations of 50–280 microplastics per kilogram. The most commonly identified polymers were polyethylene-terephthalate (PET), polypropylene (PP), and polyethylene (PE). Additionally, Fadare et al. [117] conducted a study examining the occurrence of microplastics in table salts sourced from eight African countries. The highest concentrations of microplastics were observed in South Africa, with levels ranging from 0 to 1.33 ± 0.32 particles per kilogram of salt. Nigeria, Cameroon, and Ghana also showed detectable but lower levels of microplastics (0–0.33 ± 0.38 particles/kg each). The predominant microplastic types were identified as polyvinyl acetate, polypropylene, and polyethylene. The detection of microplastics in everyday food items like beer and milk suggests that our environment is extensively contaminated with microplastics, even in trace amounts. The summary of microplastics found in various food sources is presented in Table 4.

## 5.2. Inhalation

Inhalation of microplastics occurs when small particles of plastic are inhaled into the lungs. This mode of exposure is particularly worrisome for individuals employed in industries involved in the production or utilization of plastic products. The significance of microplastics in the atmosphere has historically been overlooked, but recent evidence has shown their presence in atmospheric fallout as well as in indoor and outdoor settings [121]. The potential health risks associated with inhalation of these microplastics become crucial when they are present in substantial quantities [122]. The size of the airborne fibrous microplastics plays a key role in determining whether they can enter the respiratory system. Plastic particles with a length less than 5 μm and a diameter smaller than 3 μm have the potential to be inhaled [123]. Although they are likely to be cleared by the mucociliary mechanism in the upper airways, the particles tend to resist clearance, ultimately resulting in exposure through the gastrointestinal tract [123,124]. Workers in industries such as plastics manufacturing, waste management, and recycling face potential exposure to elevated levels of microplastics through inhalation. Moreover, individuals residing in regions characterized by high levels of microplastic contamination may also encounter microplastics through inhalation. The presence of airborne microplastics in the environment is influenced by the extensive distribution of their sources. Primary microplastics, originating from the disintegration of synthetic rubber tires, synthetic textiles, and urban dust, are recognized as the main contributors [125]. Microplastics can become airborne and be carried long distances by wind, potentially exposing individuals who live far from the source of pollution. It is estimated that wind transfer accounts for approximately 7% of microplastic contamination in the ocean [125]. Airborne microplastics, as opposed to those found in other ecosystems, have the ability to be continuously and directly breathed into the human body, posing a possible health risk [126].

The presence of microplastics in the atmosphere has been documented by a few investigations. The estimated annual intake of microplastics by individuals in America through food varies between 39,000 and 52,000 particles depending on age and gender, and when considering inhalation, these numbers increase to 74000 and 121000 particles [127]. Dris et al. [128] conducted a study to

**Table 3**
Summary of microplastics found in plastic bottled water.

| Polymer type | Dominant particle shape | Particle size | Level of MPs (mean) | Water source | Ref. |
|---|---|---|---|---|---|
| PET, PE, butadiene | – | <5 μm | 3074-6292 particles/L | Glass | [107] |
| | | | 2649 particles/L | Single use | |
| | | | 4889 particles/L | Reusable | |
| Cellulose, PS, PP, PE | Fibres, fragments | >25 μm | – | Bottled | [111] |
| PP | Fragments, fibres, films | – | 6.5–100 particles/L | Bottled | [109] |
| PET, PS, PP | Fibres, fragments | – | 8.5 particles/L | Bottled | [112] |
| PET, PP. PE | Fragments | 5–20 μm | 14 particles/L | Single use | [110] |
| | | | 118 particles/L | Reusable | |
| | | | 50 particles/L | Glass | |
| | | | 11 particles/L | Beverage carton | |

**Table 4**
Microplastic contamination in various food sources.

| Food source | Polymer type | Dominant particle shape | Level of MPs | Ref. |
|---|---|---|---|---|
| Beer | – | Fibres, fragments, granules | 2-79 fibres/L<br>12-109 fragments/L<br>2-66 granules/L | [113] |
| Beer | PP, PS | Quasi-spherical particles, irregular fragments | 20–80 | [115] |
| Wine | – | Fibres, fragments, minerals | I83 particles/L | [118] |
| Tea | PE, PET | Fibres | 200-500 items/g | [115] |
| Tea | Nylon, PET | – | 11.6 billion MPs/cup | [119] |
| Honey | – | Fibres, fragments | 40-660 fibres/kg<br>0-38 fragments/kg | [114] |
| Sugar | – | Fibres, fragments | 217 fibres/kg<br>32 fragments/kg | [114] |
| Table salt | PET, PE, PP | Fibres | 50-280 MP/kg | [116] |
| Table salt | PVA, PP, PE | Fragments, fibres, granules, paste, pebbles | 0.67–342 particles/kg | [117] |
| Sea salt | PET, PE, CP | Fragments, fibres | 550-681 particles/kg | [120] |
| Lake salt | CP, PET, PB | Fragments, fibres, pellets, sheets | 43-364 particles/kg | [120] |
| Rock/well salt | CP, PET | Fragments, fibres, pellets, sheets | 7-204 particles/kg | [120] |

investigate microplastics in an urban context, specifically focusing on their deposition from the atmosphere. The research found that microplastics, primarily in the form of fibers, were being continuously deposited at higher rates in urban areas, with a deposit of 2–355 particles per square meter per day. According to a chemical analysis, about 29% of the fibers were synthetic or a blend of synthetic and natural materials. The study extrapolated the findings and determined that the Parisian agglomeration receives between 3 and 10 tons of fiber annually as a result of atmospheric fallout. In another study, Dris et al. [129] examined the existence of fibers, highlighting their ubiquitous nature across a range of habitats. Along with outdoor air monitoring, indoor sites were explored, including private apartments and an office. The study estimated fiber concentrations, deposition rates, and their accumulation in settled dust. Indoor concentrations ranged from 1.0 to 60.0 fibers/$m^3$, while outdoor concentrations were lower at 0.3 to 1.5 fibers/$m^3$. Deposition rates indoors varied from 1586 to 11,130 per square meter per day, leading to fiber accumulation in settled dust (190–670 fibers/mg). Fibers primarily consisted of natural materials (67%), notably cellulosic, with the remaining 33% containing petrochemicals, mainly polypropylene. These studies shed light on the various sources of microplastics and provide insights into their patterns of deposition, emphasizing the significance of the atmospheric compartment as a pathway for microplastic contamination.

A recent study conducted in Shanghai, China, by Geng et al. [130] evaluated the inhalation exposure of microplastics (MPs) to humans, specifically focusing on indoor air. The study involved the participation of thirty volunteers, and their indoor aerosol (HIA) and exhaled breath (HEB) samples were taken and subjected to micro-Raman imaging spectroscopy for analysis. All samples contained microplastics, with an average concentration of $43 \pm 16$ items/$m^3$ for HIA and $12 \pm 5$ items/$m^3$ for HEB. The predominant microplastics detected were fiber-like particles and tiny fragments. The anticipated daily intake of MPs through HIA was approximately 704 $\pm$ 254 items, primarily depositing in the airways (526 $\pm$ 203 items), while the projected daily expulsion through HEB was 178 $\pm$ 75 items. The study suggests that relying solely on HIA-based approaches may overestimate daily inhalation exposure to MPs by 1.33 times, especially for smaller MPs ($<$10 μm). Therefore, it is recommended to consider integrating both HIA and HEB measurements to assess individual MPs exposure through respiration.

Microplastics in a range of 88–605 particles per 30 g of dry dust have been detected in the dust of Tehran [131]. The study revealed that engaging in outdoor activities and workspaces can expose children and adults to an estimated average of 3223 and 1063 particles annually, respectively. Amato-Lourenço et al. [26] examined the occurrence of microplastics in human lung tissues obtained during autopsies and assessed any possible harmful impacts on the respiratory system. Out of the 20 tissue samples analyzed, polymeric particles and fibers were detected in 13 samples. The fibers were found to range from 8.12 to 16.8 μm, while the particle sizes were smaller than 5.5 μm The study suggests that the diverse characteristics of these inhaled contaminants may have detrimental effects on human health, although the specific nature of these effects is still unknown.

### *5.3. Dermal contact*

Dermal contact occurs when microplastics come into contact with the skin. Humans can come into contact with microplastics through contaminated water during activities such as washing or through the use of facial or body scrubs that contain microplastics [132]. The exposure happens when microplastics enter the skin through its pores, although the extent of this exposure can vary among individuals due to variations in the size and characteristics of their skin pores [133]. According to Revel et al. [132], the probability of microplastic absorption through the skin is low because the particles must penetrate the stratum corneum, which only permits the passage of particles smaller than 100 nm. Nonetheless, it is essential to take into account the potential penetration of nanoplastic, which consists of even smaller plastic particles, as this possibility should not be dismissed. Workers in industries such as plastics manufacturing and waste management may come into contact with microplastics through direct skin contact. This exposure can lead to skin irritation and other health issues. People who participate in leisure activities in areas where microplastic pollution is prevalent may also encounter microplastics through direct contact with their skin. These activities encompass swimming, fishing, and boating, among others. Although no study has definitively established these claims, it is important not to disregard the potential for these possibilities.

Microplastic particles can also enter the human body indirectly via the use of personal care items like face cleanser, soap, toothpaste, and scrubs [134]. A study revealed that a significant percentage of face wash products (50%) and facial scrubs (67%) contained microbeads [133]. These microbeads, when present, can lead to skin aging and the development of dark spots by creating small openings that allow bacteria to enter the skin.

## 6. Health impacts of microplastics

Although the health effects of microplastics are currently under investigation, studies indicate that exposure to these minute plastic particles can potentially lead to various adverse impacts on human health [135,136]. The different reported health impacts associated with exposure to microplastics are discussed in this section according to their source of ingestion. The effects of human exposure to microplastics on health are depicted in Fig. 3.

### 6.1. Ingestion

Exposure to microplastics through ingestion has been linked to a number of health impacts, including gastrointestinal issues, endocrine disruption, and toxicity.

#### 6.1.1. Gastrointestinal problems

Gastrointestinal problems have emerged as a significant health concern associated with the exposure to microplastics. Research suggests that the ingestion of microplastic particles, either through contaminated food or water, can lead to various gastrointestinal issues [137]. These problems may include inflammation of the digestive tract, constipation, irritable bowel syndrome, disruption of gut microbiota, and alterations in intestinal permeability [137,138]. Additionally, it has been discovered that microplastics build up in the digestive system, where they may result in physical irritation and blockages [139]. It is anticipated that the cellular impacts of microplastics in the gastrointestinal tract arise from their adjuvant activity, which means they can enhance the immune response to biomolecules that are adsorbed onto their surfaces [140]. Microplastic exposure has significant implications for the symbiotic relationship between hosts and the natural gut microbiota community, leading to a disturbance known as dysbiosis. Dysbiosis can have detrimental effects on the host's immune system, potentially leading to chronic diseases, increased vulnerability to pathogenic infections, and modifications in the gut microbiota's genetic capability and expression [141,142].

The presence of microplastics in zebrafish resulted in several harmful effects within their intestines, such as mucosal damage, heightened permeability, inflammation, and disturbances in metabolic processes [138]. High concentrations of microplastics led to changes in gut bacteria, increased inflammation, and alterations in immune cell populations [143]. Recent studies have also investigated the effect of microplastic digestion by humans. Visalli et al. [144] studied the impacts of different-sized microplastics (3 μm and 10 μm) on human intestinal cells. The findings revealed that both sizes of microplastics caused moderate cytotoxicity, with the smaller particles having a more pronounced effect on cell membranes. Cells exposed to larger microplastics exhibited elevated levels of

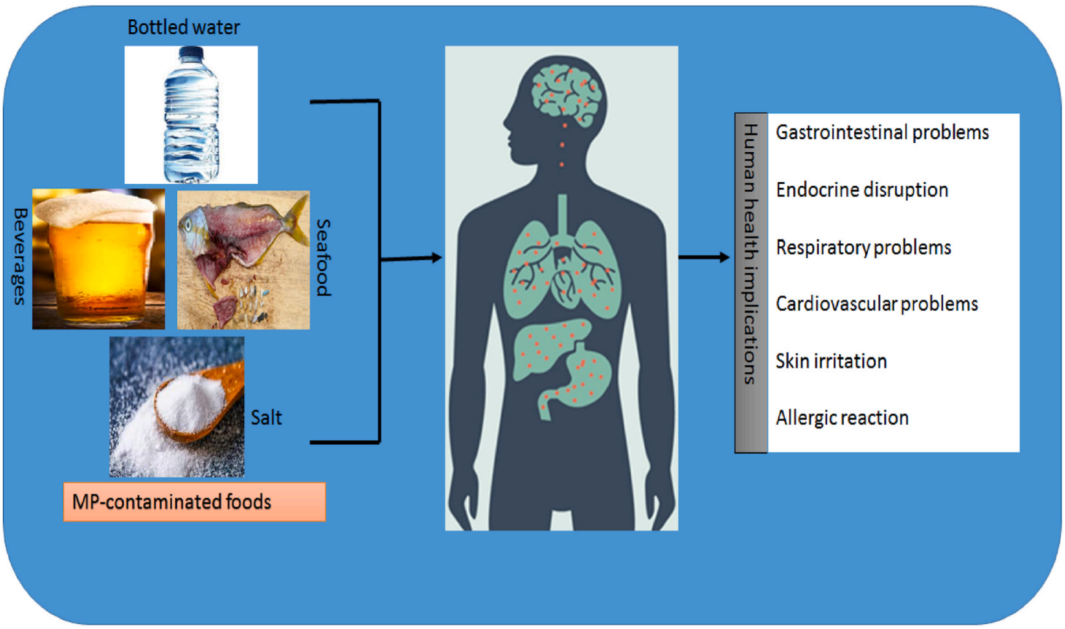


**Fig. 3.** Sources of microplastic exposure in humans and the resultant health effects.

reactive oxygen species (ROS) production; however, the cells demonstrated a partial ability to mitigate this effect over time. Prolonged exposure to microplastics could potentially lead to intestinal disorders due to increased cell mortality.

In a recent study that revealed the first possible polymer breakdown during human digestion, Tamargo et al. [145] examined the effects of microplastics on the human gut microbiota and their transformations in the gastrointestinal tract. By using a combination of static and dynamic models, researchers simulated the passage of polyethylene terephthalate (PET) microplastics through the digestive system. The findings revealed that PET microplastics underwent structural alterations in the digestive system, especially within the colon. Additionally, the gut microbial community was changed by the presence of microplastics, possibly facilitating the development of biofilms. These findings suggest that microplastics may harm the digestive system. Higher concentrations of microplastics have also been detected in the feces of individuals with inflammatory bowel disease compared to healthy individuals, implying a possible link between microplastics and the development or progression of inflammatory bowel disease [146].

#### 6.1.2. Endocrine disruption

Endocrine disruption is recognized as one of the potential impacts of microplastics. Microplastics can contain and absorb various chemicals from the surroundings, including endocrine-disrupting compounds (EDCs). EDCs are substances or combinations of substances that originate externally and have the potential to interfere with the normal functioning of the endocrine system, resulting in detrimental health effects in organisms [147]. EDCs, such as bisphenol A (BPA), nonylphenol, phthalate esters, and octylphenol, are frequently used in plastics and are found in microplastics produced as additives or reaction reagents [148,149]. When ingested or in contact with organisms, microplastics can release these EDCs, which have the ability to disrupt the endocrine system. This disruption can lead to adverse effects on hormonal balance, reproductive function, development, and overall health [150,151]. The likelihood of encountering EDCs is increased by the small size and widespread distribution of microplastics.

The effect of polystyrene microplastics (PSMPs) on the bioavailability and reproductive disruptions caused by microcystin-LR (MC-LR) in zebrafish was investigated by Lin et al. [152]. PSMPs enhanced the build-up of MC-LR in zebrafish gonads and intensified the reproductive damage caused by MC-LR. PSMPs also disrupted sex hormone levels and the HPG axis, exacerbating reproductive dysfunction. PSMPs acted as carriers, enhancing the bioaccumulation and reproductive toxicity of MC-LR in zebrafish. Microplastics were found in the gastrointestinal tract of all studied Atlantic horse mackerel samples from central Mediterranean Sea [153]. The presence of vitellogenin, a biomarker indicating endocrine disruption, was detected in the liver of 60% of male specimens, highlighting the widespread ingestion of plastics by the fish species. Exposure to microplastics and associated chemicals in Japanese medaka fish led to altered gene expression and abnormal germ cell proliferation. These findings suggest that environmentally relevant concentrations of plastic debris can disrupt the endocrine system in adult fish [154].

Despite the concerning evidence regarding the potential harmful effects of microplastic additive chemicals, there is limited understanding of the leaching capabilities of these chemicals from various polymer types and their possible deleterious impact on human health [149].

#### 6.1.3. Microplastics as a pathogen vector

Like other surfaces in marine environments, microplastics rapidly attract bacteria and a diverse range of organisms, leading to the formation of complex biofilms [155]. The term “plastisphere” was first used by Zettler et al. [156] to describe the unique microbial communities that inhabit microplastic surfaces in marine environments. It is well-documented that plastic surfaces in seawater quickly form a conditioning film and subsequent biofilm, which differs in structure from the surrounding seawater [157]. When microplastics act as carriers for pathogenic bacteria, they can potentially contaminate water sources and food chains, leading to the spread of diseases [158]. Once ingested, microplastics and the associated pathogenic bacteria can accumulate in the gastrointestinal tract, potentially causing infections or inflammatory responses. Some pathogenic bacteria found on microplastics have been linked to gastrointestinal illnesses, respiratory infections, and skin diseases in humans [159,160].

A study in wastewater treatment plants in Hong Kong examining the colonization of microplastics in sewage revealed that bacterial communities formed biofilms on the surfaces of polyethylene microbeads incubated in raw sewage [161]. The study found an increase in bacterial diversity over time and identified human and fish pathogens among the bacteria on the microplastics. This indicates that microplastics can transport disease-causing bacteria in sewage. Kirstein et al. [155] successfully identified *Vibrio parahaemolyticus* on different types of microplastics collected from the North and Baltic Sea, suggesting that the colonization of Vibrio on microplastics may originate from surrounding seawater. The findings emphasize the importance of studying the distribution and persistence of these pathogenic bacteria on marine microplastics, particularly in relation to potential health risks associated with microplastic-associated microbial communities. A similar study has reported the existence of *Escherichia coli* and *Vibrio* spp. bacteria on plastic resin pellets discovered on public swimming beaches [162].

Furthermore, the presence of antibiotic-resistant bacteria on microplastics is a growing concern. These bacteria can transfer their resistance genes to other bacteria, contributing to the spread of antibiotic resistance, which poses significant challenges in healthcare and the treatment of bacterial infections [163,164]. Microplastics in a mariculture system were found to harbor antibiotic-resistant bacteria (ARB) and antibiotic resistance genes (ARGs), including multi-antibiotic resistant bacteria (MARB) [165]. The abundance of cultivable ARB on microplastics was noticeably greater compared to the levels found in water samples. *Vibrio*, *Muricauda,* and *Ruegeria* were among the prevalent ARB genera. The microplastics also exhibited resistance to multiple antibiotics, particularly penicillin, sulfafurazole, erythromycin, and tetracycline. The presence of ARGs and gene cassette arrays associated with class 1 integrons further highlighted the role of microplastics in promoting the spread of antibiotic resistance. Additionally, there is growing apprehension regarding the persistence of harmful substances like polycyclic aromatic hydrocarbons and pesticides adhering to plastics. These plastics act as carriers for these highly toxic pollutants, posing a risk of bioaccumulation within fatty tissues [166].

### 6.2. Inhalation

Exposure to microplastics through inhalation has been linked to respiratory and cardiovascular problems and other health impacts.

#### 6.2.1. Respiratory problems

Inhalation of airborne microplastics can potentially affect respiratory health. These tiny particles can cause irritation and inflammation in the respiratory tract, leading to symptoms like coughing, wheezing, shortness of breath, and exacerbation of pre-existing respiratory conditions like asthma [167,168]. Toxicity is influenced by the fibre's size. Less thick fibers can be inhaled into the respiratory system, while longer fibers have increased persistence and toxicity to lung cells. Fibers measuring 15–20 μm cannot be effectively cleared from the lungs by natural mechanisms, such as alveolar macrophages and the mucociliary escalator [169]. The most carcinogenic fibers are those that are less than 0.3 μm thick and longer than 10 μm [139]. This health impact of microplastic is of particular concern for individuals who work in industries that producing or utilizing plastic products.

Workers in the synthetic textile and flock industries who are exposed to airborne microplastics may experience respiratory symptoms associated with the onset of airway and interstitial pulmonary diseases [170,171]. Respiratory irritation has been observed in previous studies examining the lung tissue of textile industry workers, revealing the presence of synthetic fibers [172]. An investigation of flock worker's lungs exposed to nylon flock revealed that even after leaving the work environment, some cases experienced persistent interstitial lung disease and a progressive decline in lung function, leading to respiratory failure and secondary pulmonary hypertension [173]. Also, exposure to polypropylene flock in the workplace was linked to respiratory symptoms, impaired pulmonary function, increased serum cytokine levels, and indications of early interstitial lung disease, underscoring the importance of implementing medical monitoring and measures to control exposure in the polypropylene flock industry [170].

In addition, airborne fibrous microplastics possess a hydrophobic surface that enables them to absorb pollutants from the surrounding environment [174]. In urban areas, where these microplastics are found alongside vehicular contaminants, they can transport polycyclic aromatic hydrocarbons (PAHs) and toxic metals. When these contaminants are released, detrimental effects on lung health, including genotoxicity, can occur [123]. Metabolism of PAHs associated with fibrous microplastics can lead to the formation of stable and unstable DNA lesions, contributing to the potential adverse effects [123,175].

#### 6.2.2. Cardiovascular problems

Studies indicate that being exposed to microplastics may contribute to the development or worsening of cardiovascular conditions, including hypertension, atherosclerosis, and heart rhythm disorders [176,177]. These minuscule plastic particles have been observed to trigger oxidative stress, inflammation, impair endothelial function, and interfere with regular heart function, thereby elevating the likelihood of encountering cardiovascular problems [125,178]. Furthermore, the ability of microplastics to accumulate toxic chemicals from the environment adds another layer of concern, as these chemicals can also have detrimental effects on the cardiovascular system.

Animal models are commonly employed to investigate how microplastics contribute to cardiovascular issues. It has been shown that increasing microplastic doses reduced mammalian cell viability, increased cell metabolism, and affected genes associated with oxidative stress and inflammation [179]. A higher dose of microplastic in mice has also been shown to result in changes in the hematological system, gene expression, and pathways related to immune function and metabolism in bone marrow cells [180]. The effects of PS microplastics on the cardiovascular system was investigated by Li et al. [181] using rats. The results showed that PS microplastics increased cardiac damage, collagen production, oxidative stress, and activated the fibrosis-related Wnt/β-catenin pathway, indicating that PS microplastics can induce cardiovascular toxicity by promoting cardiac fibrosis and triggering myocardial damage through oxidative stress. Similarly, Zhao et al. [177] revealed that mice consuming PS microplastics experienced weight gain, increased fat mass, elevated fasting blood glucose and insulin levels, and insulin resistance. Gene expression and gut microbiome analysis further supported the association with adiposity. These studies highlight microplastic exposure as an unrecognized risk factor for cardiovascular disease development, specifically atherosclerosis.

Recent research has also demonstrated the association between microplastics and cardiovascular disease. Human kidney and liver cells exposed to PS microplastics showed changed gene expression of key enzymes, decreased cell proliferation, structural abnormalities, and elevated levels of reactive oxygen species [182]. Wu et al. [183] studied the occurrence of environmental particles in thrombi obtained from cardiovascular surgery patients. It revealed the accumulation of diverse particles, including synthetic materials, within the thrombi. These findings underscore the underestimated negative health effects linked to microparticle exposure and emphasize the necessity for further research in this field. Chen et al. [108] also examined the impacts of polystyrene microplastics (PSMPs) on human vascular endothelial cells. PSMPs were observed to trigger oxidative stress, apoptosis, and disruption of vascular barrier function. However, when exposed to PSMPs at realistic blood concentrations, the risk of developing atherosclerosis was not significantly increased, suggesting a low cardiovascular risk associated with PSMP exposure in humans.

### 6.3. Dermal contact

While there is currently no conclusive evidence demonstrating the adverse effects of microplastics through direct contact with the skin, the potential for skin irritation and allergic reactions cannot be ruled out.

#### 6.3.1. Skin irritation

When microplastic particles come into contact with the skin, they can cause irritation, redness, itching, and inflammation. The abrasive nature of certain microplastics and their potential to clog pores or disrupt the skin's natural barrier function can contribute to these adverse reactions [184]. Additionally, microplastics may contain additives or contaminants that further exacerbate skin irritation [185,186]. Prolonged or repeated exposure to microplastics can lead to chronic skin irritation and potentially worsen existing skin conditions. A toxicity study on rats has, however, shown that chronic exposure to PP microplastics did not result in either eye or skin irritation [186]. The possibility of this, however, cannot be ignored.

#### 6.3.2. Allergic reaction

Microplastic particles coming into contact with the skin can also result in allergens and induce immune responses. The body's immune system may perceive these foreign particles as harmful and release histamines and other inflammatory substances, leading to allergic symptoms [81,187]. These symptoms can include itching, redness, swelling, hives, and even more severe reactions like anaphylaxis in rare cases [188]. It is important to note that individuals with pre-existing allergies or sensitivities may be more susceptible to developing allergic reactions to microplastics. It has been shown that exposure to high concentrations of PP microplastics can trigger immune responses and increase hypersensitivity in cells [187]. In a separate study examining the impact of primary PS particles on human health, Hwang et al. [189] discovered that even though elevated amounts of PS particles did not trigger histamine secretion or allergic reactions in HMC-1 cells, they did result in initial-stage inflammation.

## 7. The way forward

While the existing body of research has provided insights into the potential health impacts of microplastic exposure, the extent to which these pollutants present a significant danger to human health remains unclear. Consequently, further investigations are necessary to fully understand the long-term effects associated with microplastic exposure. To address the current uncertainty in human risk assessment, it is crucial to gain a better knowledge of how microplastics can traverse the epithelial barriers of the respiratory system, gastrointestinal tract, and skin. Longitudinal studies tracking individuals exposed to microplastics over extended periods can provide insights into chronic health effects, including the development of diseases such as cancer, reproductive disorders, and neurological disorders.

Microplastics have been found to readily accumulate waterborne contaminants like toxic metals and EDCs due to their extensive surface area. This accumulation is facilitated by the hydrophobic nature of persistent organic pollutants (POPs), which are typically present in the ocean. POPs, such as polychlorinated biphenyls, polycyclic aromatic hydrocarbons, and organochlorine pesticides, are known to partition onto microplastics, further amplifying their toxic effects [75]. The presence of these contaminants on microplastics has been widely reported and is associated with increased toxicity. Nonetheless, our current knowledge regarding the precise cellular interactions and toxicity mechanisms involved in microplastic exposure remains inadequate. Recent research by Jeon et al. [190] suggests that macrophages may be the primary target cells when microplastics are ingested orally. However, the toxicity of these ingested microplastics did not manifest in Caco-2 and HepG2 cells. As a result, conducting comprehensive mechanistic investigations is crucial to unravel the intricate ways in which microplastics interact with biological systems and trigger adverse effects. By understanding the cellular and molecular mechanisms underlying microplastic toxicity, we can identify critical pathways of harm and potential targets for intervention or prevention. Moreover, exploring the combined impacts of microplastic exposure with other environmental pollutants and examining the interactions and synergies between multiple contaminants will contribute to a holistic comprehension of the potential risks to human health.

Although initiatives such as the OSPAR and HELCOM conventions [191] have made strides in regulating microplastic usage and implementing mitigation measures to reduce exposure, further action is necessary. Enhancing public awareness can play a crucial role in driving behavioral shifts, encouraging responsible consumption habits, promoting effective waste management practices, and advocating for the adoption of policies and regulations aimed at addressing plastic production, usage, and disposal.

## 8. Conclusion

The study on the effects of microplastics on human health underscores the urgency and importance of addressing this global environmental issue. By analyzing the origin and routes of microplastic contamination, it becomes clear that plastic waste, microbeads, synthetic textiles, and industrial activities are significant contributors to the discharge of microplastics into the ecosystem. These particles enter the food chain primarily through marine organisms and subsequently make their way to humans via the consumption of contaminated seafood. It is worth emphasizing that microplastic exposure can also occur through alternative pathways such as soil absorption and deposition in the air. Microplastics have been demonstrated to have adverse effects on health, including inflammation, oxidative stress, and the potential for toxicity. While the full scope of the health implications is still being studied, it is evident that addressing the problem of microplastic pollution requires action. As scientists delve deeper into the effects of microplastics on human well-being, it is important for policymakers, industry, and the public to take proactive measures to minimize exposure and mitigate the environmental and health repercussions of microplastics.

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## Consent for publication

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## 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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