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Review

인체 내 미세플라스틱의 유입 경로, 건강 영향, 법률 및 정책 고찰

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Microplastics entry routes into Humans, possible health effects, laws, and policies: A review

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요약: 우리의 환경은 5 mm보다 작은 미세한 플라스틱 부산물인 미세플라스틱(MPs)으로 가득 차 있다. 최근에는 인간의 혈액과 대변, 그리고 간, 폐, 신장과 같은 주요 장기에서도 미세플라스틱이 발견되었다. 그럼에도 불구하고, 미세플라스틱이 인체에 들어오는 주요 경로에 대한 연구는 제한적이다. 본 연구는 인간에게 미세플라스틱이 유입되는 경로와 잠재적인 건강 영향을 검토하고, 미세플라스틱 규제 법률 및 정책을 분석하였다. 2014년부터 2024년까지 펍메드, 구글 스칼라, 네이처 데이터베이스, 웹오버 사이언스에서 출판된 미세플라스틱의 인체 유입 경로, 인간에 미치는 잠재적 영향, 그리고 미세플라스틱 처리에 관한 법률과 정책에 대한 67개의 연구 논문을 선택하여 검토하였다. 첫째, 음식, 음료, 공기, 치과 제품이 미세플라스틱이 인체에 들어오는 주요 경로로 파악된다. 둘째, 미세플라스틱이 소화 시스템, 간, 신장, 신경독성, 내분비 시스템, 호흡기 시스템, 인지 행동 변화, 불안, 해마 및 기억 기관의 염증에 해로운 영향을 미칠 수 있다는 것이 관찰되었다. 셋째, 아프리카, 아시아, 유럽, 미국의 여러 국가에서 미세플라스틱에 대한 법률과 규정이 통과되고 시행되었다. 여기에는 플라스틱 제품 판매 금지와 개인 위생 제품에서 미세 비즈 사용 금지가 포함된다. 그러나 미세플라스틱과 인간 건강 간의 복잡한 관계로 인해, 미세플라스틱의 축적 패턴과 장기적인 영향을 완전히 이해하기 위해서는 추가 연구가 필요하다.

주요어: 미세플라스틱, 유입경로, 인간, 건강영향

ABSTRACT: Our environment is filled with tiny byproducts of plastic smaller than 5 mm, known as microplastics (MPs). Recently, MPs have been identified in human blood and faeces, and within vital organs such as the liver, lung, and kidney. Even so, limited studies have been done on the primary pathways by which MPs enter the body. This study reviews the pathways and potential health effects of MPs in humans, MP regulatory laws and policies. 67 research publications on the routes by which microplastics enter the human body, their possible effects on humans, and the laws and policies for handling MPs, published between 2014 and 2024, were chosen and examined from PubMed, Google Scholar, the Nature database, and Web of Science. First, it was observed that food, drinks, air, and dental products are the dominant pathways of MPs into the human body. Second, it was observed that MPs in humans can be destructive to the digestive system, liver, kidneys, neurotoxicity, endocrine system, respiratory system, cognitive behavioral changes, anxiety, and inflammation of the hippocampus, and a memory organ. Third, more MP (microplastic) laws and regulations which have been passed and implemented in several countries in Africa, Asia, Europe, and America. These includes bans on the sale of plastic products and outlawing the use of microbeads in personal hygiene products. However, future research is necessary to fully understand the accumulation patterns, and long-term effects of MPs in humans because of the complex relationship between these MPs and human health.

Key words: microplastics, entry pathways, humans, health effects

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1. Introduction

Plastics have become an integral part of human everyday life (Yang *et al*., 2021). They are used practically in everything from furniture to furnishing, clothing to utensils, food packaging to water bottles, carry bags, wraps, straps, detergents, and personal care products. Plastics are omnipresent across the environment, including terrestrial, aquatic, aerosol, and biota on land and water (Haque and Fan, 2023; Kumar *et al*., 2023). Plastics are known to cause severe environmental pollution when not properly handled and recycled (Alsabri *et al*., 2022). They degrade over time into small pieces of less than 5 mm, known as microplastics (MPs) (Lee *et al*., 2023). MPs are any synthetic solid polymers with regular or irregular shapes and a size ranging from 1 μm to 5,000 μm (Frias and Nash, 2019). The MPs can be of either primary or secondary origin.

The MPs are microscopic with variable density; some of them are buoyant in seawater, have a low glass transition temperature (Rossatto *et al*., 2023; Gunaalan *et al*., 2024), and cannot be easily filtered out of the environment (Hale *et al*., 2020). According to an estimate by Eriksen *et al*. (2014), there were 35,500 metric tons of MPs floating in the ocean among the estimated 5.25 trillion plastic particles and almost 50% of the global wastewater influent of $3,562,082 \times 10^5$ m^3 remains untreated. Some conservative estimates indicate that treated effluent disposal can add around 1.47×10^{15} m^3 MPs annually, whereas the discharge of untreated effluent is likely to add a staggering 3.85×10^{16} m^3 MPs annually to the aquatic environments (Uddin *et al*., 2020).

Most published literature shows that MPs are found in all environmental compartments, such as terrestrial, atmospheric, and marine, which can end up in the human system. In a study conducted by Zhang *et al*. (2021), MPs were discovered in the faeces of adult and newborn babies. Research has indicated that MPs between 1-10 μ m may be attached to lipid membranes, that are the last protective barrier of a cell from the environment (Wang *et al*., 2022b), while others have indicated that <10 μm MPs can pass through cell membranes and enter the bloodstream (Wu *et al*., 2019). In another experimental study in mice, it was observed that particles of ≤ 1.14 μm cross the brain-blood-barrier (Kopatz *et al*., 2023). Other studies have successfully identified the presence of MPs in the heart, blood, and lungs of human beings (Chen *et al*., 2022; Leslie *et al*., 2022; Yang *et al*., 2023). However, there are limited studies on what mechanisms could be responsible for health issues caused by MPs. Some studies suggest that MPs and associated additives or adsorbed pollutants may have toxic effects on human cells, tissues, and organs. Investigating their potential toxicity is crucial for risk assessment and public health protection (Lee *et al*., 2023).

To reduce the health risks threats that MPs pose to humans, regulations and laws that control their presence are imperative (Carlos *et al*., 2021; Sorensen *et al*., 2023). Aside from ensuring less MP (plastic) pollution, effective laws and regulations also encourage safer production methods and proper trash disposal, all of which protect public health and preserve natural habitats for future generations. There are, however, few studies that address MP law and regulations.

This review paper aims to give an in-depth analysis of all the pathways by which MPs enter the human body and their potential health impacts, laws and policies for MP regulation. This information will be helpful to improve our understanding of MP pathways in humans their health implications. Determining the precise health consequences linked to MP exposure requires an understanding of the intricate interactions between size-specific MPs, the chemicals associated with them and cellular barriers. We aim to illustrate how MPs and human health are related, aiding in the development of techniques to lessen the potential risks of entry.

2. Material and methods

2.1. Data selection and categorization

Original research articles from PubMed, Google Scholar, the Nature database, and Web of Science were chosen, analyzed, and discussed to elucidate the MP pathway in humans and the related health impacts, regulations, and policies (Fig. 1; Clarivate, 2024). A cross-sectional methodology was employed to choose recent original research publications that described human MP health impacts, legislation, and regulations, as well as the sources of MPs in humans. Not every article that search engines recommended was taken into account for this study's discussion

(Chia *et al*., 2023a). Original studies that do not provide a sufficient explanation for the sources of MP in humans and the effects of MP occurrence on human health, laws, and policies are excluded. These procedures guaranteed equitable representation and accessibility of the chosen papers, which helped to ensure that the goal of this study was achieved without bias (Chia *et al*., 2023b).

Papers published between 2014 and 2024 were chosen based on keywords like "microplastic in humans," "microplastic effect in humans", "pathways of microplastic in humans," "sources of microplastic in humans," plastic control laws," "policy for microplastic," and "microplastic laws,". A total of 507 manuscripts were identified [150 articles (search term: microplastic in humans {excluded correction papers, meeting papers, letters, proceeding papers, and early access papers}) + 71 articles (search term: microplastic effect in humans) + 13 articles (search term: pathways of microplastic in humans) +41 articles (search term: sources of microplastic in humans) + 15 articles (search term: policy for microplastic) + 135 articles (search term: plastic control laws) + 3 articles (search term: microplastic laws)].

At the beginning of the investigation, all of the original research publications were selected using thirteen different database categories, specifically "Marine Freshwater Biology," "Toxicology," "Food Science Technology," "Ecology," "Oceanography," "Fisheries," "Public Environmental Occupational Health," "Chemistry Multidisciplinary," "Soil Science," "Engineering Environmental," "Green Sustainable Science

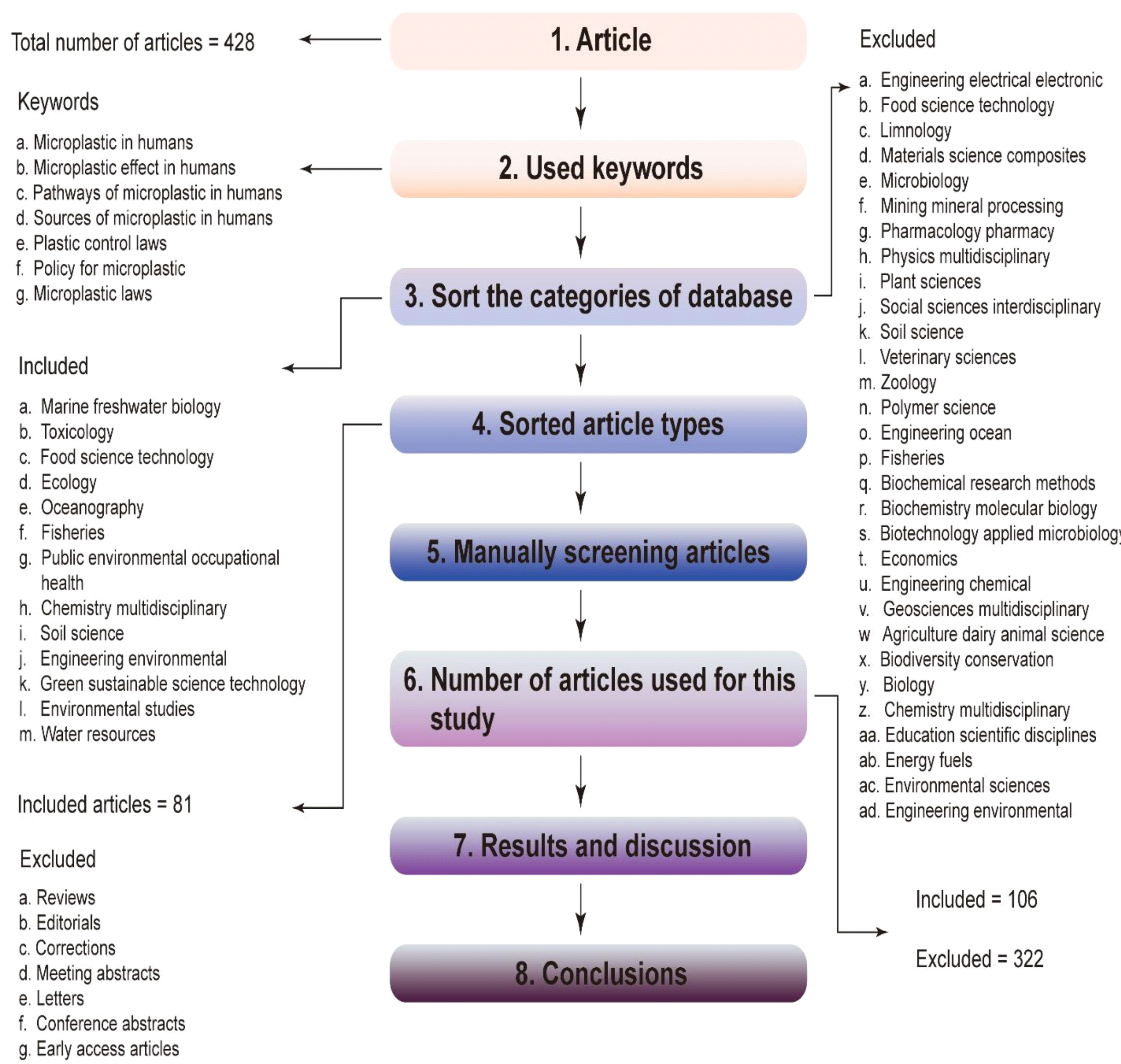

Fig. 1. The systematic method employed to choose scientific publications in this study.

Technology," "Environmental Studies," "Water Resources," from PubMed, Google Scholar, Nature's database, and Web of Science (WoS).

To assure the accuracy of the 428 papers obtained, all studies underwent a rigorous screening process that included only original research articles with a certain degree of acceptable error. The majority of the selected articles omitted studies that could not provide evidence of human MP pathways and the related health impacts, legislation, and regulations. Moreover, original research studies that did not demonstrate the direct sources of MP pollution or its effects on humans but merely documented MP contamination in humans were disregarded. After the 428 publications were filtered, 106 were selected as the main dataset to address human MP pathways and related health impacts, as well as legislation, policies, and future directions for research (Fig. 1).

3. Results and discussion

3.1. Microplastic pathways into humans by ingestion

One of the most basic routes through which MP particles enter the human body is by ingestion. The ingestion of MPs by humans can be through various products such as; food, beverages, water bottles, drinking water, and more (Fig. 2). The ingestion of MPs can occur through the following common pathways: contaminated food and water, inhalation of airborne particles, and personal health products.

3.1.1. Drinks and bottles

Various studies have documented the presence of MPs in beer, drinking water, and other beverages (Table 1). This can be attributed to the tendency of drinking water to be exposed to pollution from natural sources, air depo-

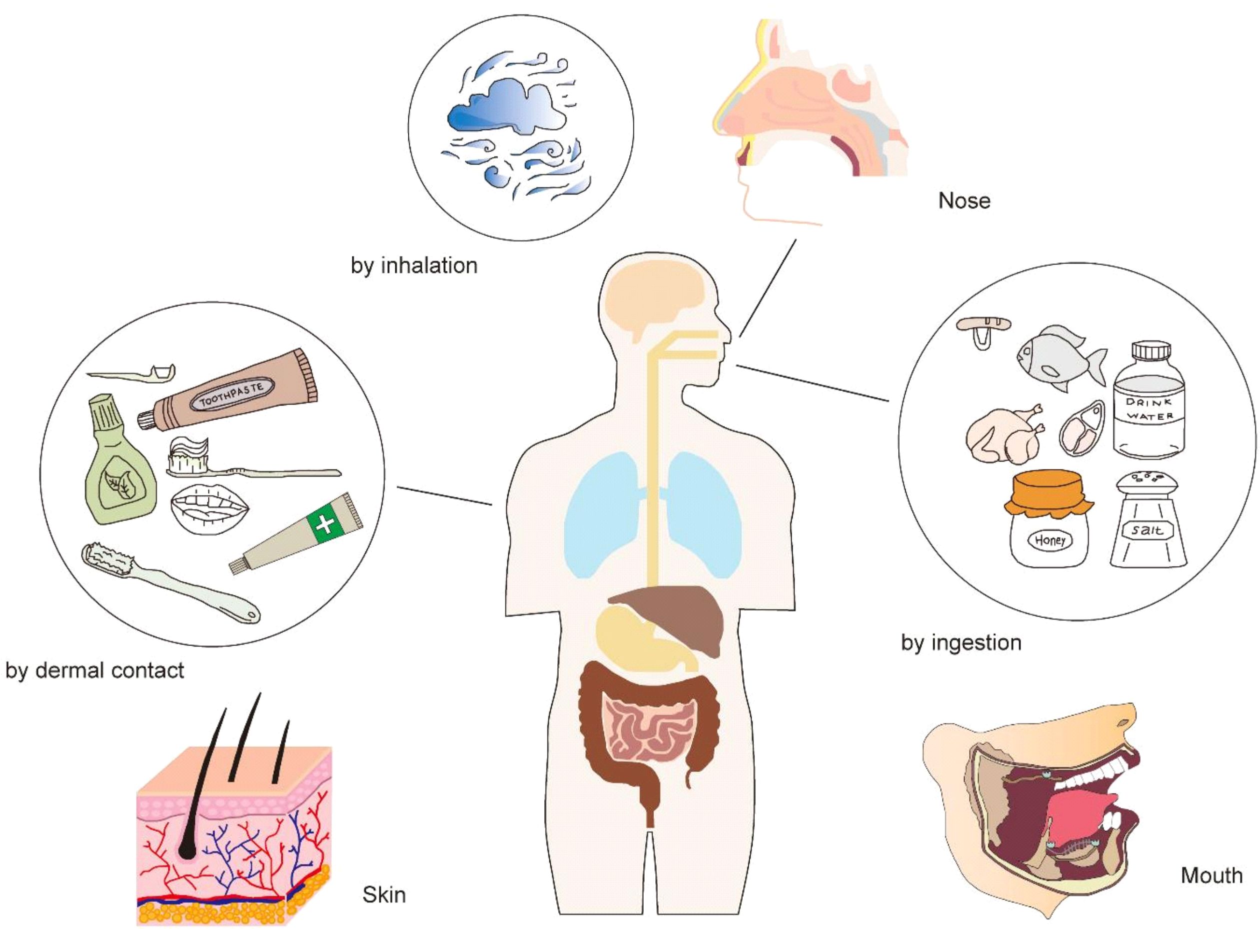

Fig. 2. Entry pathways of microplastics to the human body. (a) Nose by inhalation: both indoor and outdoor atmospheric air fallout; (b) Mouth by ingestion: Fish, meat, salt, honey, water and chicken; and (c) Skin by dermal contact: hygienic items like toothpaste, body cleansers, and scrubs.

Table 1. A synopsis of the studies on entry pathways that the systematic review included.

Author(s)	Country	Study methods	Entry pathway	Concentration (Particles/L)
Oßmann *et al*. (2018)	Germany	Micro-Raman spectroscopy	Bottle water	2,649 ± 2,857
Diaz-Basantes *et al*. (2020)	Ecuador	Fourier Transform Infrared Spectroscopy (FT-IR)	Milk, beer, soft drinks and honey	10 to 100
Tong *et al*. (2020)	China	Micro-Raman spectroscopy	Tap water	440 ± 275
Mintenig *et al*. (2019)	Germany	Fourier Transform Infrared Spectroscopy	Groundwater	0−7
Oliveri *et al*. (2020)	Italy	Italian methodology for MPs extraction and analysis, and SEM-EDX	Fruits and vegetables	195,500 ± 128,687
Gündoğdu (2018)	Turkey	Microscopic and Raman spectroscopic examination	Table salt	16−84
Iñiguez *et al*. (2017)	Spain	Stereo microscopy and Fourier Transform Infrared Spectroscopy (FT-IR)	Table salt	50−280
Yang *et al*. (2015)	China	AxioCam digital camera and Fourier Transform Infrared Spectroscopy (FT-IR)	Table salt	550−681
Alfaro-Núñez *et al*. (2021)	Ecuador	Olympus BX53	Aquatic food products	0.36 ± 0.10
Goswami *et al*. (2020)	India	Fourier Transform Infrared Spectroscopy (FT-IR)	Aquatic food products	45.17 ± 25.23
Barboza *et al*. (2020)	Portugal	Fourier Transform Infrared spectrometer (Perkin Elmer Spectrum BX spectrometer)	Fish	0.054 ± 0.099
Bilal *et al*. (2023)	Pakistan	FTIR spectroscopy (IRTracer-100, Shimadzu, Columbia, MD, USA)	Chicken	1,227
Habib *et al*. (2022)	United Arab Emirates	Fourier Transform Infrared (FT-IR) spectroscopy	Fish and chicken	2.6 ± 2.8
Kedzierski *et al*. (2020)	France	Fourier Transform Infrared microspectrometer (ATR-FTIR Lumos, Bruker)	Meat	4.0−18.7
Dris *et al*. (2016)	France	Stereomicroscope	MPs fallout	2−355
Baeza-Martínez *et al*. (2022)	Spain	Fourier transform infrared spectroscopy	MPs fallout	9.18 ± 2.45
Dris *et al*. (2015)	France	Histolab and a Leica MZ12 stereomicroscope	MPs fallout	29−280
Strand (2014)	Denmark	Fourier transform infrared spectroscopy	Dental and body scrubs	0.4−10.5
Madhumitha *et al*. (2022)	India	Fourier transform infrared spectroscopic analyses	Toothpaste	167−508
Ustabasi and Baysal (2019)	Turkey	Microscopic and surface chemistry analysis	Toothpaste	0.4−1
Praveena *et al*. (2018)	Malaysia	FTIR Spectrometer was	Personal and cosmetic products	10−178

sition, wastewater discharge, plastic manufacturing and packaging, and contamination during bottling or brewing (Lee *et al*., 2023; Bhardwaj *et al*., 2024; Haleem *et al*., 2024). Water that is produced and processed using plastic caps, containers, and other packaging materials consist of MP particles. Also, MPs can be introduced during the brewing and bottling operations of beverages, such as beer (Jin *et al*., 2021; Crosta *et al*., 2023). This can be associated with exposure to plastic equipment or packing materials which come into direct contact with the beer and increase the likelihood that MPs will be present in the finished product (Cha *et al*., 2023).

In a study conducted by Oßmann *et al*. (2018), water from all types of bottles, including glass and single-use and reusable polyethylene terephthalate (PET) and PET-based bottles, was found to contain MPs. In glass bottles, the number of MPs in the mineral water ranged from 6,292 ± 10,521 per litre to 2,649 ± 2,857 per litre in single-use PET bottles (Oßmann *et al*., 2018). A similar study in China on the prevalence of MPs in tap water found that tap water contained varying amounts of MPs, ranging from 0 to 1,247 particles L^{-1} and the main MPs comprised polyethylene and polypropylene (Mintenig *et al*., 2019; Tong *et al*., 2020). Also, research by Mintenig *et al*. (2019) shows the abundance of MPs in drinking water from groundwater sources.

3.1.2. Food

Food is one of the body's main sources of energy, so by eating, humans ingest MPs from contaminated food sources. A few major causes of the MP contamination of these foods are the use of wastewater for irrigation, sludge application in agriculture fields, bioaccumulation, processing and packaging, plastic mulching, and air deposition (Schell *et al*., 2022; Udovicki *et al*., 2022; Hassan *et al*., 2023). According to numerous studies, MPs can seep into food from packaging materials (made from plastic), which increases the risk of human consumption (Habib *et al*., 2022). The handling and processing of food also plays a role in the contamination of MPs, particularly in areas where plastic packaging is widely used. Strict laws governing food packaging materials are necessary, as evidenced by the persistence of MPs in food products.

The use of MPs in plastic mulching to improve crop growth can result to MP deposition in soils (Bläsing and Amelung, 2018). Microplastics in soil can pass through plant roots and move to other areas of the plant, including the edible sections (Wang *et al*., 2022a). MPs may appear in fruits and vegetables as a result of this process, called bioaccumulation (Oliveri *et al*., 2020). A study on the prevalence of MPs in fruits and vegetables shows that apples were the most contaminated fruit and carrots were the most contaminated vegetable. The carrots samples contained the smallest MPs (1.51 μm), whereas the lettuce samples had the largest MPs (2.52 μm) (Oliveri *et al*., 2020). Recent studies on the presence of MPs in milk, beer, and honey shows that the MP concentration ranged from 10 to 100 MPs/L, with an average of about 40 MPs/L (Diaz-Basantes *et al*., 2020; Zhang *et al*., 2020; Milne *et al*., 2024). The presence of MPs in honey can be linked to the processing, packaging, use of plastic in beehives, and airborne MPs. MPs can enter the environment through the water and air and eventually settling on soil and plants (Chia *et al*., 2023c). Bees may come into contact with MPs on the surfaces of flowers and plants when they are foraging for nectar and pollen. In a study, the MP concentration ranged from 10 to 100 MPs/L, with an average of about 40 MPs/L, and fragments between 2.48 and 247.54 μm found in honey were confirmed based on Fourier transform infrared spectroscopy (FTIR) composition analysis (Diaz-Basantes *et al*., 2020).

Salt is also one of the sources of MPs (Gündoğdu, 2018; Kuttykattil *et al*., 2023; Canga *et al*., 2024). According to the study results, the MP particle content was 16-84 item/kg in sea salt, 8-102 items/kg in lake salt, and 9-16 items/kg in rock salt. The most common plastic polymers were polyethylene (22.9%) and polypropylene (19.2%) (Gündoğdu, 2018). The principal reasons that MPs are found in salt are associated with air deposition, marine activities, pollution in the environment, and contamination during salt harvesting and processing (Peixoto *et al*., 2019; Kuttykattil *et al*., 2023). MPs may be introduced via the processing and shipping of salt products, particularly in regions where plastic is widely used. During these procedures, the salt could become contaminated by MP particles from the packaging materials (Karami *et al*., 2017).

A similar study was also carried out in Spain on the prevalence of MPs in salt, and the reported MP content found was 50-280 MPs/kg of salt, with polyethylene-terephthalate (PET) being the most frequently found polymer, followed by polypropylene (PP) and polyethylene (PE) (Iñiguez *et al*., 2017). Similarly, a study by Yang *et al*. (2015) found that in sea salts, the MPs content was found to be 550-681 particles/kg, while in lake salts it was 43-364 particles/kg, and in rock/well salts it was 7-204 particles/kg. In contrast to pellets and sheets, fragments and fibres were the most common types of particles found in sea salts. The majority of the particles, or 55% of all the MPs, were smaller than 200 µm. The most prevalent MPs in sea salts were polyethylene terephthalate, followed by polyethylene and cellophane (Yang *et al*., 2015).

Humans rely on the aquarine environment as one of the sources of food which serves as a pathway for MP transfer through trophic levels. A study by Alfaro-Núñez *et al*. (2021) points out the MP pollution of seawater and marine organisms and reports that marine organisms and water samples contained MP particles. The majority of the MP particles ranged in size from 150 to 500 µm (Alfaro-Núñez *et al*., 2021). Widespread plastic contamination in the aquatic environment has resulted in the occurrence of MPs in marine creatures, including fish. MPs in marine creatures are largely derived from a variety of sources, including plastic breakdown in the ocean, atmospheric deposition, plastic waste in water bodies, and ingestion by plankton and rivers as conduits of MPs from inland areas to seas. Fish may ingest MPs and tiny pieces of plastic that mimic prey directly and it may consume these particles believing them to be food (Eryaşar *et al*., 2022).

The ingestion of MPs by marine organisms in a study in India discovered that the average concentrations of MP in sediment, water, finfish, shellfish, and zooplankton were 0.93 ± 0.59 particles per m^3, 45.17 ± 25.23 particles per kilogram, 0.12 ± 0.07 pieces per zooplankter, and 10.65 ± 7.83 particles per specimen, respectively (Goswami *et al*., 2020). In the zooplankton community, a high level of MP retention was found. *Carangoides malabaricus* adults were found to consume the most MPs (Goswami *et al*., 2020; James *et al*., 2020). A recent study in Portugal by Barboza *et al*. (2020) reveals that the ingestion of MPs by fish shows that, of the 150 fish examined (50 for each species), 49% had MP. Within the gastrointestinal tract, gills, and dorsal muscle of fish belonging to the three species, MP was discovered. A total of 0.054 ± 0.099 MP items/g, or 32% of the 150 fish that were analyzed, had MP in their dorsal muscle (Barboza *et al*., 2020). In another study in Kuwait, MPs were reported in the gastrointestinal tract of eight most consumed fish species in Persian Gulf (Al-Salem *et al*., 2020). However, the occurrences were very low, with only three fragments detected within the guts of *Acanthopagrus latus*, *Eleutheronemaa tetradactylum* and *Lutjanus quinquelineatus,* despite their preference for staying in muddy waters and sheltered lagoons, which have comparatively higher MP concentrations. Microplastics were also reported from *Chelon aurata* and *Rutilus kutum*, the two fish species that account for over 50% of the total Caspian Sea catch. Out of the 111 individual samples analysed, 67.56% were positive for MPs, with an average of 2.29 MP/Fish (Zakeri *et al*., 2020). The dominant spare reported was fibres (≈50%) and fragments (≈30%).

In a similar study by Habib *et al*. (2022), fish samples showed a range of MP contamination: from 0.014 ± 0.024 to 2.6 ± 2.8 particles per gram, and from 0.03 ± 0.04 to 1.19 ± 0.72 particles per gram of meat in chicken. A variety of factors, including environmental contamination, feed, water, and human activity, can cause MPs to enter the food chain and eventually make their way into chicken and meat. By consuming contaminated feed, water, livestock including chickens, may swallow MPs, which eventually end up on human tables and cause discomfort to the human system. It was determined that the plastic cutting board made of polyethene, which was used to cut the food, was the source of the MPs. When food was cut from the bone rather than the fillets itself, and the fillets were prepared on surfaces other than plastic, there was more MP contamination present (Habib *et al*., 2022).

Meat, chicken and dairy products are contaminated by packaging materials. According to Kedzierski *et al*. (2020), food products are contaminated with MPs at a level that varies from 4.0 to 18.7 MP/kg of packaged meat. These MPs are most likely from the PS trays, according to analysis. These particles are probably cooked before consumption and are challenging to remove with simple washing (Kedzierski *et al*., 2020). Chicken as a source of food is one of the main entry pathways of MPs into the human body. As per on study in Pakistan, 1,227 MP particles in all were discovered in 24 samples (gizzards and chicken crops) that came from the 8 chicken farms. A total of 24 chicken crops contained 429 MP particles, with a mean of 17.8 ± 12.1 MPs/crop. On the other hand, 24 chicken gizzards exhibited 798 MP particles, with a mean of 33.25 ± 17.8 MPs/gizzard. Particles measuring between 300 and 500 μm were found to be more common (63%) than those with sizes between 300 and 150 μm (21%) and 150 and 50 μm (16%) (Bilal *et al*., 2023).

3.2. Microplastic pathways into humans by inhalation (air)

According to studies by multiple authors, MPs are found in both outdoor and indoor (atmospheric) environments where humans inhale them (Lee *et al*., 2023). For example, in a recent study by Zhang *et al*. (2020), several indoor settings revealed the presence of MP fallout. Both megacities and sparsely populated areas have recorded air fallout with high levels of MPs (Gasperi *et al*., 2018). These MPs originated from the degradation and fragmentation of textile and plastic bags and bottles (Prata, 2018; Sun *et al*., 2020). There are several reasons why MPs are present in the air, which may be attributed to industrial processes, atmospheric deposition, and automobile emissions. These particles may come from the manufacturing and processing of plastics, which can contaminate the air near industrial regions (Chia *et al*., 2021). Furthermore, the usage and deterioration of consumer plastic goods, including furniture, packaging, and synthetic textiles, greatly increase the amount of MPs in the atmosphere. Due to normal wear and tear, these products may leak MPs into the atmosphere and thus, inhaled by man. A study conducted in the urban and sub-urban sites of Paris observed that there was an atmospheric fallout of 2-355 particles/m^2 per day (Dris *et al*., 2016). Comparing the urban and sub-urban sites, the registered fluxes at the former were consistently higher. The amount of these entirely synthetic fibres (made with petrochemicals) or a combination of natural and synthetic material can be estimated at 29% thanks to chemical characterization (Dris *et al*., 2016).

A similar study in Spain by Baeza-Martínez *et al*. (2022) reports that a concentration of 9.18 ± 2.45 items/100 mL was found to be the average concentration of MPs, with microfibers (MFs) making up 97.06% of all MPs (Baeza-Martínez *et al*., 2022). There was no significant correlation found between MPs and clinical, physiological, or environmental factors, and only 5.88% of MPs were particulate MPs, with an average concentration of 0.57 ± 0.27 items/100 mL. The polyacrylic fibre measured 9.96 mm in its longest length, and the average dimensions were 1.73 ± 0.15 mm (Baeza-Martínez *et al*., 2022). MPs were also observed in atmospheric fallout with the overall amount of atmospheric fallout (29-280 particles m^{-2} day^{-1}) highlighting the presence of MPs, primarily fibres (Dris *et al*., 2015). In another study, MP in aerosols was reported from Kuwait, where a six-stage cascade impactor was deployed to sample indoor aerosol. The study reported 3.2 and 27.1 MPs/m^3 (Uddin *et al*., 2022). The MP concentration decreased linearly from the lowest to the highest size fraction. The fibres were the most dominant shape, followed by fragments in lower-size fractions.

3.3. Microplastic pathways into humans by dermal contact and sanitary products

Using hygiene and dental products is another way that MP enters the body through dermal contact because many mouth washes, toothpaste and sun creams contain microplastics for their exfoliating properties (Chang, 2015; Madhumitha *et al*., 2022; Chengappa *et al*., 2023). This area of research is not very well explored; however, some studies have revealed the presence of MPs in the sanitary products and dental hygiene products we use daily (Table 1). MPs have long been used in exfoliating scrubs, face cleansers, and body washes, the grainy texture felt is often microbeads. Using sanitary products is a significant additional way that people are exposed to MPs (Rochman *et al*., 2015). In order to improve the texture, exfoliating qualities, or aesthetic appeal of the product, these MPs are purposefully included (Cheung and Fork, 2017; Alex *et al*., 2024; Aristizabal *et al*., 2024). MPs are used as abrasives in some toothpaste formulations to clean teeth. For example, polyethene microbeads have been utilized because of their abrasive qualities (Anagnosti *et al*., 2021). These goods have the potential to discharge MPs into the environment and come into close contact with human skin. MPs may be able to cross the epidermal barrier and enter the body, thereby increasing the risk of exposure for humans, depending on their size and makeup (Ma *et al*., 2024).

To fully evaluate the hazards associated with MP exposure and create mitigation methods for any potential health effects, it is essential to comprehend the mechanisms and exposure routes, such as dermal contact and the use of sanitary goods. A straightforward route for MPs to enter the human body is through dermal contact (Aristizabal *et al*., 2024). People come into contact with MPs through routine activities like handling plastic-based products, touching contaminated surfaces, and going into places both indoors and outdoors where MPs are present. By making physical touch with the skin, these particles may stick to the skin and possibly be absorbed through the pores (Campanale *et al*., 2020; Sun and Wang, 2023). Studies indicate that some forms of MPs may be able to pass through the skin barrier and into the bloodstream, raising worries about potential health impacts even though the extent of dermal absorption of MPs is still being investigated.

In a study of 9 selected dental and body products, MP was found in nine products that were said to contain polyethene (Strand, 2014). Dental pastes contained between 0.1 and 0.4% of it, compared to scrubs' 0.4-10.5%. Particles ranging in size from 40 to 800 μm were found in the products (Strand, 2014). A study conducted in India revealed that the most prevalent types of microparticles in toothpaste were colourless fibres and fragments, with weights ranging from 0.2 to 0.9% and an abundance range of 32.7-83.2% (Madhumitha *et al*., 2022). Looking at the 50% abundance in some toothpastes, it is clear that they are added by manufacturers. The MPs examined in this study had sizes ranging from 3.5 to over 400 μm (Madhumitha *et al*., 2022). Similar research studies in Turkiye and Malaysia established the presence of MPs in scrubs, kinds of toothpaste and facial cleaners (Praveena *et al*., 2018; Ustabasi and Baysal, 2019). More research activities are required to gain a deeper comprehension of the processes involved in MP absorption via the skin, their dispersion throughout the body, and their long-term effects on human health.

4. Microplastic exposure impacts on human health

In recent years, research articles on the effects of MPs on organisms have received widespread attention (Szymańska and Obolewski, 2020; Daghighi *et al*., 2023). However, few clinical and laboratory studies have been conducted on the effects of MPs on human health (Fig. 3). Most research studies are based on in vivo and in vitro clinical trials on mice and simulated effects of possible consequences for the human health system (Table 2).

4.1. Microplastic impacts on the internal system

An infestation of MPs is bad for the human body. Seven polymers were discovered in the excrement of patients in a study that looked into whether MPs were damaging to the vascular system (Yan *et al*., 2023). Compared to patients without vascular calcification (VC), patients with VC had higher concentrations of polypropylene (PP), polystyrene (PS), and total MPs in their feces (Yan *et al*., 2023). Following the exposure of a mouse to PS-MPs, a study aimed at elucidating the mechanisms underlying mitochondrial damage observed alterations in oxidative stress and examined the structure and function of the mitochondria. The results showed that MPs caused an imbalance in the homoeostasis between mitochondrial division and fusion, decreased adenosine triphosphate (ATP) content, decreased mitochondrial membrane potential, and compromised the integrity of the mitochondrial genome. MPs induced oxidative stress in cells, causing structural damage to the mitochondria (Liu *et al*., 2022).

According to a study's findings, mice that inhale PS-MPs develop pulmonary fibrosis in a dose-dependent way (Li *et al*., 2022). In the high dose group (6.25 mg/kg), the PS-MPs significantly ($p < 0.05$) increased the expression of α-SMA, vimentin, and Col1a. Furthermore, breathing in MPs made of PS induces oxidative stress and triggers the Wnt/β-catenin signaling pathway in mice, leading to pulmonary fibrosis (Li *et al*., 2022). MPs were found to be more concentrated in the stools of people with inflammatory bowel disease than in the stools of healthy people in a study that examined the presence of MPs in various human organs, tissues, or matrices and their effects on animal and human health. MPs in liver tissues were detected exclusively in cirrhosis patients (Barceló *et al*., 2023).

A research study combined a harmonized static model and a dynamic gastrointestinal simulator model to simulate the effects of a single dosage of PET on the digestive system (Tamargo *et al*., 2022). The findings showed that several biotransformations were triggered by PET in the digestive system. There was a structural difference between them and the original particles at the colon. The study suggests that gut health may be negatively impacted by MPs (Tamargo *et al*., 2022). In a comprehensive anal-

Table 2. A synopsis of the studies on health-related effects that the systematic review included.

Author (s)	Country	Organism/setting	Potential health effect
Peng *et al*. (2023)	Belgium	In vitro	Oxidative stress and mitochondrial dysfunction
Cheng *et al*. (2024)	China	In vitro	Cytotoxicity and disruptions to the gene responsible for iron transport and use.
Weingrill *et al*. (2023)	Brazil	In vitro	Placenta as a bioaccumulation assay of MPs. No proven effects on maternal or fetal health
Yan *et al*. (2023)	China	Patients	Vascular calcification (VC)
Yin *et al*. (2023)	China	In vitro	Liver inflammation
Xu *et al*. (2019)	China	Invitro	Effects on the respiratory system
Tamargo *et al*. (2022)	Spain	In vitro	Biotransformations were triggered by PET MPs in the digestive system. The study suggests that gut health may be negatively impacted by microplastics
Liu *et al*. (2022)	China	In vivo	Microplastics induced oxidative stress in cells, causing structural damage to the mitochondria.
Barceló *et al*. (2023)	Saudi Arabia	Patients	Inflammatory bowel and cirrhosis.
Li *et al*. (2022)	China	In vivo	Pulmonary fibrosis and induced severe oxidative stress in the lungs.
Lee *et al*. (2022)	Taiwan	In vivo	Neuroinflammation and behavioral changes
Kaur *et al*. (2023)	India	In vivo	Anxiety and changes in cognitive behavior
Amereh *et al*. (2020)	Iran	In vivo	Endocrine disturbance and reproductive toxicity
Xiong *et al*. (2023)	China	In vivo	Kidney disease

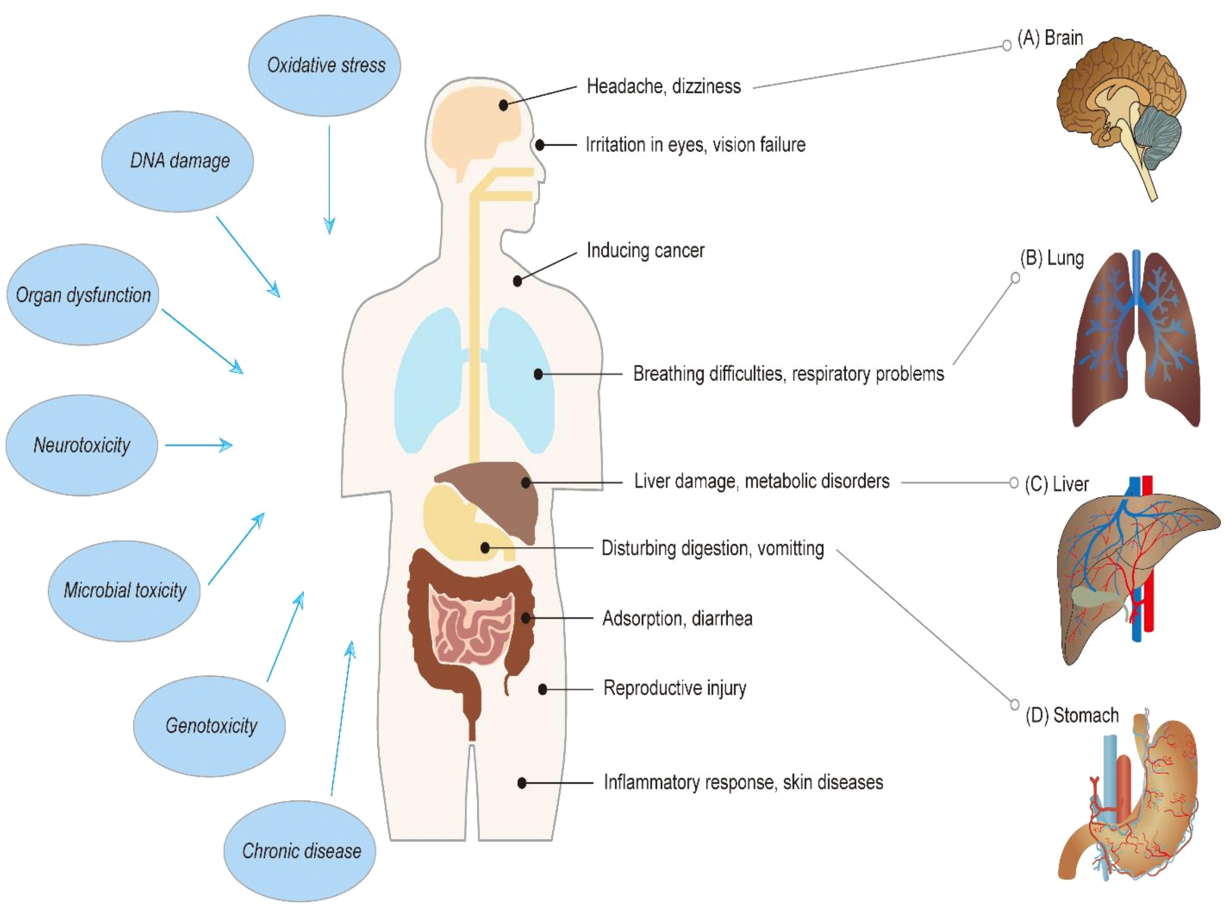

Fig. 3. Impacts of microplastics on human health.

ysis to investigate the cellular and bioenergetic effects of MPs under varied exposure scenarios, four distinct types of human cell lines derived from the lung (A549 and BEAS-2B), colon (Caco-2), and liver (HepG2) were utilized. Even after the initial exposure period, PS was found to have long-term effects on mitochondrial and cellular functions. In particular, Caco-2 cells exposed to a single PS dose for 12 days exhibited elevated levels of mitochondrial dysfunction and oxidative stress (Peng *et al*., 2023).

MPs can disrupt growth and reproduction by interfering with the endocrine system (Amereh *et al*., 2020). This might result in low fertility rates among people, which would be catastrophic for the population. MPs can accumulate in the respiratory system and induce inflammation of the respiratory system (Xu *et al*., 2019). Within the human respiratory system, MPs have the ability to change the expression of proteins linked to the cell cycle and initiate the transcription of genes that cause inflammation. Chronic obstructive pulmonary disease (COPD) and asthma are two respiratory disorders that can arise from the respiratory system's stimulation of inflammatory gene transcription (Xu *et al*., 2019). Research by Xiong *et al*. (2023), suggested that exposure to MPs made of PS could cause oxidative stress in humans, which would impair kidney function. According to Yin *et al*. (2023), PS caused inflammation in the liver and the development of macrophage extracellular traps (METs). This shows that lysosomal damage may play a major role in the creation of METs that PS-MPs generate.

4.2. Microplastic impacts on the external behaviour

Consuming MPs has the potential to alter behavior. In a study conducted to find out if adult male Swiss albino mice's behavior is affected by exposure to different amounts and timings of PS, it was found that animals exposed to PS behaved differently from control animals (Kaur *et al*., 2023). Less open field exploration, more entries, and more time spent in the elevated maze's closed arms were some of these modifications. These alterations in behavior are a sign of elevated anxiety, which implies that MPs may be inducing stress reactions in the central nervous system (de Figueiredo Cerqueira *et al*., 2023). The elevated plus maze and open field test are common tools used to gauge anxiety-like behavior in mice, and the changes in these behaviors that have been seen offer compelling proof of the neurobehavioral effects of MPs. These actions suggested that the animals were experiencing anxiety due to PS. Additionally, mice administered PS displayed altered cognitive behaviour (Kaur *et al*., 2023). Learning and memory recall were found to be problematic for the exposed mice in cognitive behaviour assessments, including maze navigation and object identification tasks. This suggests the possibility that MPs could disrupt the neuronal mechanisms that underlie cognition.

In a related study, mice exposed to MPs showed changed expression of genes and synaptic proteins that are connected to neural activity. The hippocampal region showed signs of increased neuroinflammation, which can trigger vagus nerve-dependent behavioural changes. Pro-inflammatory cytokines, which have been shown to impact behaviour and brain function, can be released as a result of neuroinflammation in the hippocampus (Kim *et al*., 2016). One important way that MPs cause anxiety and cognitive impairments may be through this inflammation. Findings made clear how harmful MPs are to the hippocampal region, which is in charge of memory and learning (Lee *et al*., 2022).

Additional studies are required to prove a causal relationship between human behavioural or cognitive changes and MPs. More thorough data could be obtained via experimental investigations with greater sample sizes and a wider range of demographic backgrounds. In order to create more distinct connections, research should also look for signs of MP exposure and related neurobehavioral alterations. Individual sensitivity as well as the kind, size, and chemical composition of the particles are among the factors influencing the potential health effects of MPs (Ivleva, 2021). These factors make risk evaluation more difficult because different kinds of MP may differ in their level of toxicity. For example, different chemical additions in plastics may have varied toxicological profiles, and smaller particles may be able to pass through biological membranes more readily (Barceló *et al*., 2023; Ma *et al*., 2024). The relationship between human health and MPs is a complex one. It takes an interdisciplinary approach to completely understand this link and to thoroughly unravel the causes and effects of MP exposure, combining neurology, toxicology, environmental science, and epidemiology.

Table 3. Summary laws and guidelines on microplastics and plastics in certain countries.

Country or Region	Year of adoption	Policy/Regulation	Author (s)
European Union	2023	Restrict microplastics intentionally added to products under the EU chemical legislation.	EU (2023)
United States of America	2015	This law prohibited the use of plastic microbeads in manufacturing, packaging, and distribution of cosmetics.	Sorensen *et al*. (2023)
United Kingdom	2017	Ban in the use of microbeads on personal health products.	Hirst and Bennett (2017)
China	2020	Nationwide ban on production and sales of daily chemical products containing plastic microbeads.	Liu and Liu (2023)
Korea	2018	Ban on the sale of cosmetics including microbeads	Song (2016)
Cameroon	2012	Ban on the manufacture, import and marketing of non-biodegradable packaging.	Tabeyang (2018)
Democratic Republic of Congo	2018	Prohibits the import, production, consumption and use of plastic bags and packaging	Carlos *et al*. (2021)
Canada	2024	Ban on microbeads in Toiletries Regulations	Canada (2024)
Australia	2018	Agreement to phase-out of microbeads in personal care, cosmetic and cleaning products	AG (2018)
Japan	2019	Japan Action Plan for Marine Plastic Litter	Kato *et al*. (2021)

5. Laws and policies on microplastics and plastics

Global environmental concerns over MPs have led to the implementation of laws and policies by many countries to alleviate their negative effects (Table 3). To reduce pollution, the European Union has adopted measures, passing laws on purposefully inserted MPs in a range of goods. In the US, several states have placed limitations on the use of microbeads in personal hygiene products, and federal legislation deals with more general concerns related to marine debris. A proposed nationwide plan to eliminate plastic pollution was released by the United States Environmental Protection Agency (USEPA) in April 2023. Three objectives are included in this draft strategy, one of which is to particularly stop MPs and nanoplastics from getting into waterways (Table 3). In 2018, Canada began to forbid the production and importing of any toiletries that include microbeads. Moreover, in 2020, Canada suggested a new approach for managing plastic waste. The ultimate objective of this all-inclusive management system is to lower the quantity of MPs and their discharge into the environment. Australia began to phase out the use of microbeads in rinse-off cosmetics and personal hygiene products in 2020. Launched in 2021, the Australian National Plastics Plan lays out a strategy to eventually phase plastics out of the Australian economy completely. It entails doing away with harmful plastics, clearing plastic from beaches and the oceans, passing laws ensuring trash accountability, funding recycling infrastructure, funding research, and maintaining recycling support (Table 3).

Several Organisation for Economic Co-operation and Development (OECD) and non-OECD nations have implemented measures to reduce the amount of plastics that leak into the environment in response to growing concerns about the risks associated with plastic pollution. These include better waste management practices, outlawing frequently littered single-use plastic items, and placing limitations on the production and distribution of specific personal care and cosmetic products that contain MPs. Despite making up a sizable portion of all releases into the environment, MPs released from automobile tyres and textile items are still primarily outside the purview of current regulatory frameworks. This is mostly explained by the new nature of research into mitigation methods and the technological difficulty of preventing unintended losses of MPs during product use (Shardul *et al*., 2023).

To address plastic pollution, particularly MPs, the United Kingdom has outlawed the production of rinse-off personal care products containing microbeads (Table 3). This is indicated in the Environment Bill. Recently, the United Kingdom Water Industry Research (UKWIR) suggested intervention control for the wastewater sector. This covers modifications to labelling, increased producer accountability, prohibitions, grants, and subsidies for reusable items, as well as adjustments to public infrastructure like the provision of disposal containers for garbage. Recognizing the damaging impacts of MPs on the environment, nations like China, Japan, and Korea (Republic of) are putting regulations to manage plastic waste into place throughout Asia. For instance, the Chinese government has been increasingly concerned about plastic pollution at both the national and subnational levels since the early 2000s, and this concern has increased significantly since 2016. In order to limit plastic pollution and provide alternatives to plastics, China has rules under the Law on the Prevention and limit of Environmental Pollution by Solid Wastes (LPCEPSW) that classify plastic pollution under solid waste. In addition to encouraging a circular economy, the restrictions forbid the disposal of plastics in aquatic environments. The Chinese province of Hainan, for instance, declared that non-biodegradable plastic products will be prohibited after 2025. Certain African nations, like the Democratic Republic of the Congo and Cameroon, have outlawed the production and import of plastic packaging. Increasingly, countries are enacting policies to limit the use and discharge of MPs into the environment as the international community recognizes the need to eliminate this pollution (Table 3).

Current legislation and industry-led initiatives have mostly concentrated on laying the groundwork for comprehensive and empirically supported mitigation frameworks. These frameworks frequently include a variety of components, such as funding for research projects, to fill in knowledge and data gaps regarding the prevalence of MPs in the environment and the risks they pose to human and environmental health. Additionally, efforts to raise consumer awareness and educate them about sustainable product usage are being made in an effort to change consumer behavior by encouraging the adoption of methods that reduce the emission of MPs during product use. Furthermore, a crucial component of these regulations has been enabling the exchange of data and information through multistakeholder platforms in order to promote research and encourage cooperation across industries.

In the process of designing policy, it may be necessary to provide more specific information about the working mechanisms. It will be beneficial to understand the precise level of MP infestation in the human body to develop trustworthy and efficient policy measures regarding the effects of MPs on human health. Reliable quantification of MP concentrations in human tissues may result in improved health and safety recommendations and regulations, as well as well-informed policy decisions.

6. Conclusion and recommendations for future studies

Three primary routes exist for MPs to enter the human body: ingestion, inhalation, and dermal contact. Of these, ingestion is the most frequent entry point, according to this review paper. In vivo or in vitro studies made up the bulk of research on the effects of MPs on human health. Although the reviewed studies exhibit heterogeneity, there is a dearth of research articles explaining the primary cause of various illnesses as MPs. Larger studies that investigate various aspects of the invasion consequences of MPs into the human body are suggested to be necessary by the review's findings. In-depth knowledge regarding potential risks associated with MP accumulation is provided by this review paper to individuals, educators, institutions, and policy makers.

In terms of global MP research activities and initiatives, China holds the top spot. As the world's second-biggest economy, China produces a lot of plastic goods for both domestic and international markets. Nowadays, China has a very well-established legislative system that aims to reduce pollution from plastic through increased infrastructure and solid waste management, an overhaul of city planning, and the circular economy as a whole. China has made tremendous progress in source control capability in recent years by progressively establishing a marine plastic pollution prevention system. It was also observed that many African nations lack feasible research initiatives related to MPs. To sum up, while this work advances our knowledge of MPs pathways and their possible health effects on the human system, further research is still needed to fill in the knowledge gaps on the degree to which MP infestations drive human system disorders. The following investigations are necessary:

1) To determine whether any demographic group is more susceptible than others to the buildup of MPs.

2) More research is needed to determine which human organs are more vulnerable to MP buildup.

3) To assess MP exposure's long-term health effects and whether MPs serve as carriers of other pollutants or illnesses.

4) To assess the intricate connection between MPs and detrimental health outcomes in the human body, future research should include longitudinal investigations.

5) To assess MPs in Africa because inadequate knowledge could impede the worldwide understanding of MP pollution's spread and impact because of the region's distinct environmental and socioeconomic characteristics, which may have varied effects on MP pollution and distribution.

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