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A systematic review of the impacts of exposure to micro- and nano-plastics on human tissue accumulation and health

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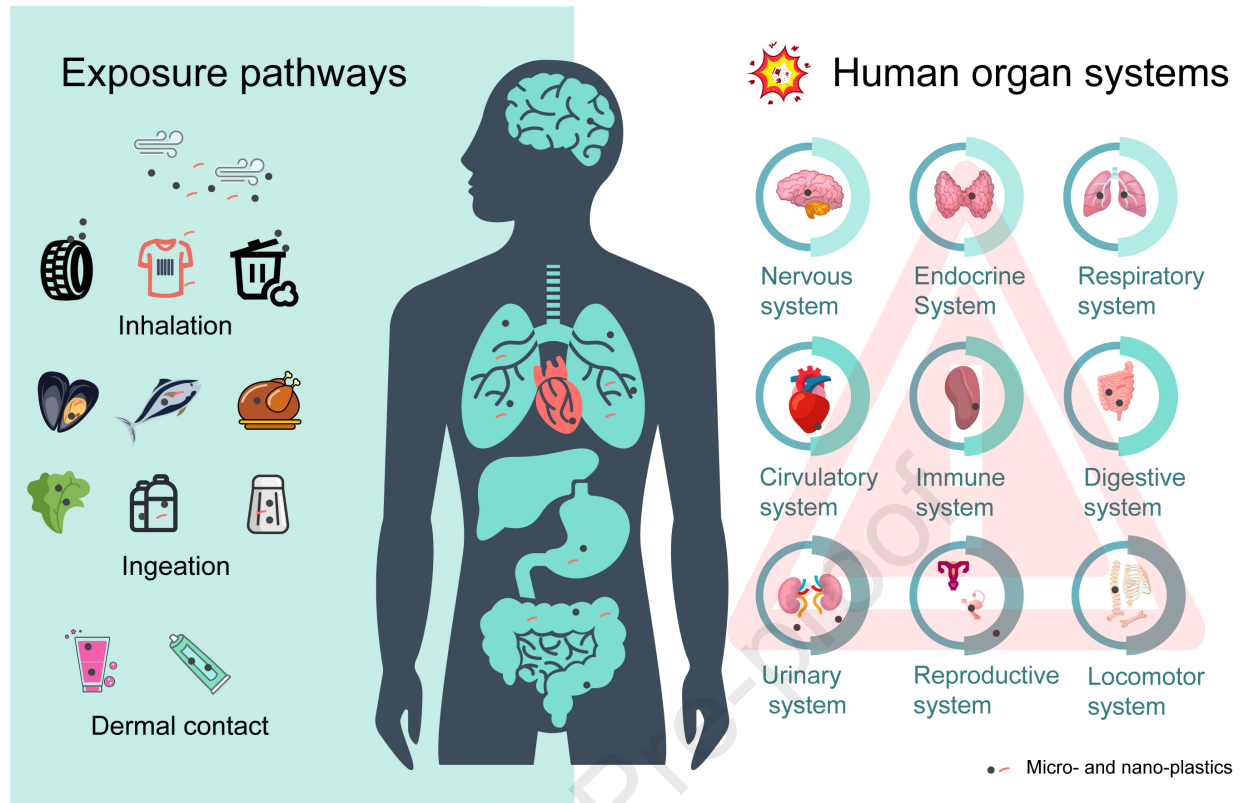
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A systematic review of the impacts of exposure to micro- and nano-plastics on human tissue accumulation and health

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1 **Abstract:** Micro- and nano-plastics (MNPs) pollution has become a pressing global environmental
2 issue, with growing concerns regarding its impact on human health. However, evidence of the
3 effects of MNPs on human health remains limited. This paper reviews the three routes of human
4 exposure to MNPs, which include ingestion, inhalation, and dermal contact. It further discusses the
5 potential routes of translocation of MNPs in human lungs, intestines and skin, and analyses the
6 potential impact of MNPs on the homeostasis of human organ systems, and provides an outlook on
7 future research priorities for MNPs in human health. There is growing evidence that MNPs are
8 present in human tissues or fluids. Lab studies, including *in vivo* animal models and *in vitro* human-
9 derived cell cultures, revealed that MNPs exposure could negatively affect human health. MNPs
10 exposure could cause oxidative stress, cytotoxicity, disruption of internal barriers like the intestinal,
11 the air-blood and the placental barrier, tissue damage, as well as immune homeostasis imbalance,
12 endocrine disruption, and reproductive and developmental toxicity. Limitedly available
13 epidemiological studies suggest that disorders like lung nodules, asthma, and blood thrombus might
14 be caused or exacerbated by MNPs exposure. However, direct evidence for the effects of MNPs on
15 human health is still scarce, and future research in this area is needed to provide quantitative support
16 for assessing the risk of MNPs to human health.

17 **Keywords:** Micro- and nano-plastics; Environmental exposure; Human system homeostasis; Health
18 effects; Risk assessment

19

20 1. Introduction

21 Microplastics (MPs) are plastic fragments with a particle size of ≤ 5 mm, while nanoplastics
22 (NPs) are typically considered to have a particle size of ≤ 1 μm [1]. Despite consistent efforts to
23 reduce plastic manufacturing and enhance plastic recycling, an estimated 250 million metric tons
24 (Mt) of plastic waste will enter the aquatic system and 460 million Mt will enter the soil system
25 from 2016 to 2040 [2]. Plastic waste that enters the environment includes primary micro- and
26 nanoplastics (MNPs), such as those added to personal care and cosmetic products [3], as well as
27 secondary MNPs produced by the fragmentation of larger plastics through physical, chemical and
28 biological processes [4]. MNPs are ubiquitous in the global biosphere and can be found in oceans
29 [5], lakes [6], rivers [7], indoor air [8], outdoor air [9], and soil [10], as well as in seafood [11],
30 drinking water [12], beverages [13], and salt [14].

31 Humans are inevitably and continuously exposed to MNPs, raising concern about their
32 potential risk to human health [15-19]. However, it is unclear whether MNPs directly affect human
33 health, due to limitations in human tissue sampling, lack of epidemiological investigations and of
34 *in situ* detection methods. Current studies have shown that MNPs not only exhibit particulate
35 toxicity to organisms but also induce chemical toxicity [20, 21]. The toxicity of particles with similar
36 sizes to MNPs, such as PM_{10} (aerodynamic equivalent diameter less than 10 μm), $\text{PM}_{2.5}$
37 (aerodynamic equivalent diameter less than 2.5 μm), and engineered nanoparticles, has extensively
38 been studied [22]. Epidemiological studies have shown a significant correlation between $\text{PM}_{2.5}$ and
39 human respiratory morbidity and mortality [22]. In addition, long-term exposure to engineered
40 nanoparticles can cause lung damage and cardiovascular disease [23]. To date, there is a paucity of
41 epidemiological studies examining the potential health effects of MNPs in humans. However,
42 available evidence from *in vitro* studies using human cells and *in vivo* studies using animal models,
43 such as mice and rats, indicates that exposure to MNPs may induce inflammation, oxidative stress,
44 cytotoxicity and respiratory disease [24, 25]. Moreover, it is important to note that MNPs not only
45 contain a range of plastic additives, including dyes, plasticizers, and antioxidants, but also serve as
46 carriers of persistent organic chemicals, heavy metals, and pathogenic microorganisms, all of which

47 can be toxic and have potential carcinogenic and mutagenic effects on human health [20, 26]. There
48 is thus an urgent need to understand the potential impact of MNPs on human health.

49 We collected and analyzed the available literature mostly published before June 2023 based on
50 the database of Web of Science, ScienceDirect and Google Scholar using the keyword
51 “microplastics” OR “nanoplastic”, and the articles were grouped with different categories including
52 “atmosphere or air”, “seafood, drinking water, salt, sugar or honey”, “translocation or
53 accumulation”, “system, lung, intestinal or placenta”, and “toxicity, human, cell or rat” to
54 summarize the new progresses. We found that MNPs have been detected not only in human feces
55 [27], urine [28], and sputum [29] but also in the lungs [30] and intestines [31]. Moreover, they have
56 been found to enter the blood [32], thrombus [33], closed body fluids [34], liver [35], and even the
57 placenta [36]. Meanwhile, the number of studies on the impact of MNPs on the health of model
58 animals or human cells has exponentially increased, yielding fresh insights into our understanding
59 of the effects of MNPs on human health. This review aims to discuss the exposure pathways of
60 MNPs, the potential uptake, transport, and accumulation mechanisms of MNPs in the human body,
61 and the potential toxicity to human organ systems. By summarizing current knowledge, this review
62 hope to provide insights for further research to better understand the impact of MNPs on human
63 health.

64 **2. Pathways of exposure of MNPs to humans**

65 In order to evaluate the impact of MNPs on human health, it is crucial to elucidate the pathways
66 and levels of human exposure. The three primary routes of human exposure to MNPs are inhalation,
67 ingestion, and dermal contact. Therefore, it is imperative to thoroughly investigate these pathways
68 and their associated exposure levels to accurately assess the potential risks and hazards of MNPs to
69 human health.

70 **2.1. Inhalation**

71 **2.1.1. Indoor air**

72 It is estimated that individuals spend approximately 89% of their daily time indoors,
73 highlighting the significance of MNPs concentration in indoor air to human health [8]. The different
74 functions of indoor spaces affect the abundance of MNPs. In Paris, the abundance of MPs ranged
75 1.1–18.2 fibers/m³ in apartment air and 4.0–59.4 fibers/m³ in offices [9]. In nail salons, the
76 abundance of MPs in the environment is 46 particles/m³ [37]. The deposition rate of MPs also varies
77 in different indoor environments, with the highest in the home [up to 1.96×10^4 particles/(m²·day)]
78 and lowest in the classroom [6.20×10^3 particles/(m²·day)] [38]. Zhang et al. [8] detected 5.5 times
79 as many MPs in the dormitory air [9.9×10^3 particles/(m²·day)] as in the office [1.8×10^3
80 particles/(m²·day)]. The abundance or deposition rate of MPs in indoor air can vary significantly
81 from room to room. This variation is primarily influenced by factors such as the room's function,
82 the flow of people, and the concentration of MPs in the outdoor air [8]. The variability can be
83 attributed to differences in the detection methods employed by researchers [8, 9]. Additionally, Zhan
84 et al. [39] detected an abundance of MPs in the indoor air of electronic waste dismantling facilities,
85 ranging from 2.6 to 11 particles/m³. These MNPs pose a greater risk to human health, as they may
86 contain flame retardants, heavy metals, or poly-brominated diphenyl ethers (PBDEs). Currently,
87 researchers mainly used two methods of collection, active and passive sampling, but the data from
88 both methods cannot be compared because passive sampling can only respond to the amount of
89 MNPs that can be deposited in the air [40]. At present, the majority of MPs in indoor air are fiber
90 with sizes >20 μm [41]. Future research needs to focus on MNPs with particle sizes <2.5 μm, as
91 suspended MNPs with smaller particle sizes are more easily inhaled by people.

92 Infants or children tend to spend more time indoors compared to adults [42]. However, the
93 abundance of MPs in indoor air below 1 m is very poorly documented. In addition, infants and
94 children are more likely to inhale or ingest indoor dust, which also contains high levels of MPs.
95 Concentrations of polyethylene terephthalate (PET) and polycarbonate (PC) in indoor dust in 12
96 countries ranged from 38 to 1.2×10^5 μg/g and < 0.11 to 1,700 μg/g, respectively [43]. In Shiraz,
97 the abundance of MPs in school dust was 195 particles/g [44]. Therefore, different living situations
98 and ages need to be considered when assessing the health risks of MNPs in indoor air to humans.

99 2.1.2. Outdoor air

100 The outdoor environment is more extensive, and the air is more mobile than indoors. The
101 concentration of MNPs is generally lower in the outdoor environment compared to indoors. In
102 Wenzhou, China, the outdoor abundance of MPs (189 ± 85 particles/m³) was one order of magnitude
103 lower than indoors ($1,583 \pm 1,180$ particles/m³) [45]. Similarly, in Paris, France, the abundance of
104 MPs in indoor and outdoor air range 1–60 particles/m³ and 0.3–1.5 particles/m³, respectively [9].
105 The abundance of MPs in outdoor air exhibited regional differences, with MPs being more abundant
106 in urban air than in rural air, and in northern Chinese cities than in southern cities [45, 46]. For
107 example, Liu et al. [47] estimated that Shanghai residents inhaled approximately 21 particles/day
108 outdoors, while in Wenzhou, urban residents inhaled 3,360 particles/day from outdoor air, and 1,515
109 particles/day for rural residents [45]. MPs in outdoor air have a considerably smaller impact on
110 human health than in indoor air. However, further investigation of the concentrations of MNPs in
111 the air around sites such as roads, construction sites or landfills is needed to assess the potential
112 health risks of MNPs to people living or working in these environments.

113 Based on the above information, people are constantly inhaling MNPs, but the amount of
114 MNPs inhalation into the body remains uncertain. Zhang et al. [48] roughly estimated the annual
115 human inhalation of MPs through indoor and outdoor air to be 1.9×10^3 – 1.0×10^5 and 0 – 3.0×10^7
116 particles, respectively. However, they overlooked the variations in daily respiration rates among
117 different demographic groups, including men and women, as well as adults and children. Cox et al.
118 [42] further subdivided the population, with the highest amount of MPs inhaled annually by adult
119 males at 6.2×10^4 particles and the lowest amount by female children at 3.9×10^4 particles. However,
120 there is still a great gap between the current estimate and the actual amount of MNPs inhaled by
121 human beings. On the one hand, human beings will still exhale some of the MNPs when they breathe
122 out, and on the other hand, the concentration of NPs in the air is still unknown in general.

123 2.2. Ingestion

124 2.2.1. Seafood

125 MNPs have been found in over 690 marine species, including the seafood humans regularly
126 consume, such as fish, mollusks, and crustaceans [49-51]. Nearly half of the 338 fish species
127 investigated contained MPs, with an average abundance of 3.5 ± 0.8 particles/fish [52]. MPs are
128 predominantly detected in fish intestines but rarely in fish meat [52]. In contrast, mollusks such as
129 oysters, mussels, and clams are consumed whole by humans. The highest abundance of MPs in
130 oysters is 99.9 particles/individual in some waters with high MP contamination [53]. Mollusks
131 obtained on the market contain fewer MPs than mollusks caught directly, presumably because the
132 marketed soft-bodied creatures have been cleaned [54]. Crustaceans, such as crabs and shrimp, also
133 have edible and inedible parts. The inedible parts (4.4 particles/animal) primarily consist of the
134 stomach and gills, which contain an average concentration of MPs four times that of the edible parts
135 (1.2 particles/animal) [55]. To minimize exposure, it is advisable not to consume the intestines and
136 stomachs of shrimp or crab. Additionally, when assessing human exposure to MPs through seafood
137 consumption, it is crucial to focus on the edible portion of the seafood for a more accurate evaluation.

138 **2.2.2. Drinking water and beverages**

139 There are significant differences in the abundance of MPs found in tap and bottled water (Table
140 1). Oßmann et al. [56] detected that the abundance of MPs in bottled water is up to $2,649 \pm 2,857$
141 particles/L in single-use PET bottles and $6,292 \pm 10,521$ particles/L in glass bottles, which is by far
142 the highest abundance of MPs in bottled water [57]. Therefore, in addition to the packaging itself,
143 other sources of contamination must also be considered, such as cleaning, packaging, and transport.
144 The majority of MPs in bottled water have a particle size between 1 and 5 μm [57]. Overall, the
145 abundance of MPs in tap water was lower than in bottled water, with the current maximum
146 abundance of MPs in tap water being 930 particles/L [58]. The effort of boiling tap water before
147 drinking fails to diminish the number of MNPs in the water [59]. Based on the available data,
148 Danopoulos et al. [12] estimated that the maximum annual intake of MPs for adults from consuming
149 tap water and bottled water was 4.58×10^5 and 3.57×10^7 particles, respectively.

150 MNPs also have been detected in beer, tea, soft drink, and milk [13, 60, 61]. The most essential
151 component of beverages is water, and the presence of MNPs in water can lead to beverage

152 contamination. Shruti et al. [60] investigated four beverage categories, and the most contaminated
153 with MPs was beer (less than 28 ± 5.29 particles/L). Li et al. [13] investigated 15 brands of beer
154 from various nations and detected that the abundance of MPs ranged from 1.2×10^4 to 9.7×10^4
155 particles/L. This is mainly due to the different identification methods used. Shuri et al. [60] did not
156 count MPs $<100 \mu\text{m}$ using microscopy, whereas Li et al. [13] counted all MPs $<5 \text{ mm}$ using
157 microscopic Raman. In addition, tea also contains MPs, especially when brewed in tea bags. During
158 the brewing process, around 50 plastic particles per tea bag will detach from the tea bags and fall
159 into the tea [62]. Milk and related dairy derivatives are one of the human body's primary sources of
160 protein and calcium, but are currently contaminated with MPs [63, 64]. The abundance of MPs in
161 milk varies considerably from country to country, with 3–11 particles/L in Brazil [63], 164–427
162 particles/L in India [64], and 2.04×10^3 – 1.0×10^4 particles/L in Switzerland [61]. In the future,
163 continuous monitoring of MNPs in drinking water and beverages will be of utmost importance.
164 Equally vital will be the establishment of appropriate standards for bottled water to effectively
165 regulate the levels of MNPs.

166 **2.2.3. Salt, sugar, and honey**

167 MNPs are present not only in food, but also in food spices like salt, sugar, and honey (Table 1)
168 [14, 65, 66]. MNPs are commonly found in different types of salt, including sea salt, rock salt, and
169 lake salt, with an abundance range from 0 to 39.8 particles/g and predominantly presenting a fibrous
170 and fragmented shape [67, 68]. The annual intake of MPs through salt consumption by adults ranges
171 from 35.8 to 36,172 particles [68]. Sugar and honey also have been found to be contaminated with
172 MNPs. In Bangladesh, MPs were detected in all sugar samples, with a mean abundance of 344 ± 32
173 particles/g [65]. The abundance of MPs in honey was relatively low at 22–114 particles/L [66].
174 Other food spices (cooking oil, monosodium glutamate and soy sauce) also need to be examined for
175 the presence of MNPs to ensure food safety.

176 **2.2.4. Crops and livestock**

177 At present, MNP contamination in crops and livestock remains unknown. However, laboratory

178 studies have shown that crops can take up MNPs. In hydroponic experiments, wheat (*Triticum*
179 *aestivum* L.), lettuce (*Lactuca sativa*), and carrots (*Kurodagosun*) could take up MNPs [69, 70];
180 Moreover, in soil experiments, MNPs were taken up by lettuce (*Lactuca sativa*), rice (*Oryza sativa*
181 L.) and peanut (*Arachis hypogaea* L.) and accumulated in the stems and leaves of lettuce, the seeds
182 of rice and the peanut [71, 72]. These results raise concerns about crops in heavily MNP-
183 contaminated soils. Although crops tend to absorb few MNPs under natural exposure, long-term
184 consumption of crops containing MNPs may adversely affect human health. Livestock is not
185 immune to MNP contamination, with about 46 particles/gizzards in chicken in the family yard [73].
186 MPs were also detected in edible snails (*Helix pomatia*) [74]. Therefore, it is crucial to pay attention
187 to the risk of human exposure to MNPs through the food chain, particularly to NPs, which are more
188 likely to be transmitted through the food chain and have biomagnification effects.

189 Furthermore, the rice or meat that we purchase in our daily lives is directly sourced from the
190 market, making them susceptible to MNP contamination during production, packaging, or
191 transportation processes [75, 76]. Dessì et al. [75] detected MPs in all 52 rice samples from Australia,
192 and the average concentration of MPs in rice was $67 \pm 26 \mu\text{g/g}$ dry weight. Kedzierski et al. [76]
193 also detected MPs in packaged meat with abundances ranging from 4.0 to 18.7 particles/kg. The
194 researchers also discovered that rinsing rice with water was effective in significantly reducing MP
195 contamination [75]. However, it was observed that MPs on the surface of packaged meat were more
196 difficult to remove through simple rinsing due to their stronger adhesion to the meat [76]. Therefore,
197 washing food before consumption is necessary, especially for packaged meats that need to be
198 carefully cleaned.

199 The assessment of MNPs ingested via the ingestion exposure pathway is inherently more
200 complex than inhalation, mainly due to the wide range of food types consumed by humans. A recent
201 review has attempted to extrapolate to human exposures, reporting annual ingestion of $(0-5.5) \times 10^4$
202 particles (seafood) [77], $(0-4.7) \times 10^3$ particles (drinking water) [48], $(0-7.3) \times 10^4$ particles (table
203 salt) [48] and a mean amount of 1.9×10^{10} particles (fruit and vegetables) [78]. Furthermore, the
204 ingestion of MPs through dust should not be overlooked. According to estimates, adults have an

205 annual intake of 4.0×10^2 – 2.5×10^4 particles, while infants and young children have an annual
206 intake of 7.2×10^2 – 4.5×10^4 particles [79]. However, there is a lack of investigations on the
207 concentration of MNPs in foods such as vegetables, fruits, rice, wheat or meat. Moreover, these
208 foods are essential components of the human diet, making it challenging to accurately estimate the
209 amount of MNPs ingested through dietary intake at present. Therefore, it is crucial to take into
210 account the dietary composition of the local population and the concentration of MNPs in food when
211 evaluating the MNP intake among individuals.

212 **2.3. Dermal contact**

213 Human skin is directly exposed to MNPs, which can be detected in personal care products,
214 such as toothpaste, hand soap, face wash, and sunscreen [80, 81]. Prior to 2018, MNPs were used
215 in large quantities in personal protective equipment to replace natural substances such as pumice,
216 oatmeal, or almonds in order to exfoliate and deep cleanse the skin [82]. Concerns were raised about
217 the presence of <100 nm particles in personal skin care products that might breach the dermal barrier
218 and pose health risks [83]. In addition, plastic components in human prostheses generate MNPs as a
219 result of normal wear and tear, thereby putting them into direct contact with the skin [84]. Moreover,
220 airborne MNPs can settle with dust and come into contact with the skin [85]. To date, there are no
221 literature estimates of the amount of MNPs absorbed by dermal contact. However, due to the current
222 lack of investigation of NPs, the effects of NPs on human skin are still not negligible, especially in
223 cases where there are wounds or infections on the skin surface.

224 **3. Tissue accumulation and translocation of MNPs in the human body**

225 In recent years, MNPs have been increasingly detected in various human body fluids and
226 organs, suggesting that they can escape the body's immune cells and translocate across the
227 biological barriers into the circulatory system, eventually accumulating in organs or tissues (Table
228 2). However, restricted by ethical considerations and limited detection techniques, the translocation
229 and accumulation of MNPs in humans were scarcely investigated. This review thus refers to existing
230 knowledge of other kinds of particles which should help understand the properties of MNPs that

231 affect accumulation in the human body (Fig.1).

232 **3.1. Accumulation and translocation of MNPs in the lung**

233 Inhalation might be the most likely pathway to the human body for MNPs [48]. Various types
234 and shapes of MNPs have been found in the respiratory system, including those in the alveoli, with
235 abundance ranging from 0.56 to 1.42 particles/g [30, 86]. The mean size of these particles was
236 reported to be $1,730 \pm 150 \mu\text{m}$ [87]. These findings were obtained despite the fact that MNPs can
237 be eliminated by nasal hair blockage, mucus cilia adhesion or macrophage phagocytosis, and
238 subsequently cleared out by coughing or sputum. However, some MNPs are still able to evade these
239 clearance mechanisms, and can adhere or embed themselves, eventually accumulating in the
240 respiratory system and even translocating into circulation. [29, 88, 89]. Particle size plays a
241 significant role in the clearance, accumulation, and translocation of MNPs. Particles with sizes
242 ranging from 0.5 to $5 \mu\text{m}$ can be easily cleared through alveolar macrophages and mucus villi, while
243 larger fibers and fragments ($15\text{--}20 \mu\text{m}$) are more difficult to clear. [84, 90]. As a result, larger fibers
244 and fragments tend to accumulate in lung tissue, and the researchers detected MPs in human lung
245 tissue in the particle size range of $1.6\text{--}1,450 \mu\text{m}$ [30, 86]. Additionally, the thin and lengthy natures
246 of fibers enable their decreased mobility and increased adhesion to the lungs, consequently causing
247 lung accumulation. Respirable particles typically have a size smaller than $10 \mu\text{m}$, whereas fibers
248 that enter the lungs can reach lengths of thousands of microns, posing a long-term health hazard that
249 cannot be overlooked.

250 A small fraction of MNPs may be able to cross the alveolar wall, enter the capillaries, and
251 ultimately the bloodstream. The translocation of particles could be size-dependent. For instance,
252 studies in mice have shown that nanoparticles with sizes of up to 200 nm can pass through the air-
253 blood barrier (ABB) [91]. Similarly, human exposure experiments have found that carbon particles
254 with sizes below 100 nm can penetrate across the ABB [92]. In addition, aging can affect the
255 translocation of nanoparticles across the air-blood barrier. In neonates, the transport of gold
256 nanoparticles is not size-dependent, while in adult animals, smaller nanoparticles (5 nm) can cross
257 the ABB more efficiently than larger nanoparticles (100 nm) [93]. The ABB also can be influenced

258 by the surface charge of nanoparticles, and negatively charged particles easier cross the barrier [91].
259 NPs might cross the ABB through the large gaps formed between alveolar epithelial cells or through
260 the endocytosis of cells (Fig.1B) [94]. Further investigation is needed to determine whether MPs
261 can cross the ABB. The mechanisms by which MNPs in the environment cross the ABB are more
262 complex due to their different forms, particle size range, and surface charge.

263 **3.2. Accumulation and translocation of MNPs in the intestine**

264 MNPs that enter the digestive system are subject to a similar pathway as those entering the
265 respiratory system. When water and food containing MNPs enter the human digestive tract, the
266 intestinal tract are exposed to MNPs directly or indirectly. However, MNPs are difficult to digest
267 and degrade in the body [95]. The majority of MNPs in the human digestive tract could be excreted
268 by the body. Schwabl et al. [96] reported nine distinct types of MPs in human feces with sizes
269 ranging from 20 to 500 μm . The abundance of MPs in human feces ranged from 1 to 36 particles/g
270 [96, 97]. Surprisingly, the concentration of MNPs in infant feces was higher than in adults [98],
271 suggesting that infants and children are exposed more to MNPs than adults.

272 The researchers further found that MNPs accumulate in the human intestine and can even
273 translocate into the circulatory system. The abundance of MPs in the dead human colon was $28 \pm$
274 15 particles/g, indicating accumulation of MPs in the intestine over a long period of time [31]. MNPs
275 in the intestine could be translocated into the circulatory system through three main channels (Fig.1
276 A) [99]. The first channel involves the endocytosis of epithelial cells, which is mainly capable of
277 translocating nanoscale particles. *In vitro* experiments have demonstrated that plastic particles <100
278 nm can permeate the barrier of Caco-2 (human colon cancer)/HT29 (human cell line)+Raji-B
279 (lymphoblast-like cell line) cells and even traverse the intestinal barrier [100]. The ecological corona
280 generated by particles of plastic exposed to the environment is more conducive to the passage of
281 NPs across the intestinal barrier [101]. The second channel involves the transcytosis transport of
282 microfold (M) cells in the Peyer's patches of the ileum, which is thought to be the main mode of
283 translocation of MNPs [84, 99]. M cells can translocate particles smaller than $<10 \mu\text{m}$ to the mucosal
284 lymphoid tissue and concentrate them on the plasma membrane side of the Peyer's patch [84, 102].

285 In *in vitro* experiments, M cells co-cultured with Caco-2 cells were more likely to take up fluorescent
286 MPs than a single Caco-2 culture [103]. The third channel is the persorption process, which involves
287 the shedding of intestinal epithelial cells from their villi-like tips, and generates pores that allow big
288 particles to pass through. The experiment showed that PVC particles of 5–110 μm can pass through
289 the intestinal barrier via persorption [104].

290 However, a gap still exists between current *in vitro* cellular experiments and the actual human
291 intestinal absorption mechanism of MNPs. For instance, it is uncertain whether MNPs in the gut are
292 completely detached from food and irregular MNPs have the same fate in the gut as spherical
293 particles. Additionally, further research is needed to determine the distribution of MNPs in different
294 regions of the gastrointestinal tract, such as the small intestine, colon, duodenum, jejunum, and
295 ileum. The translocation rate of MNPs in the intestine should be further estimated through *in vivo*
296 models.

297 **3.3. Accumulation and translocation of MNPs in the skin**

298 The skin, being the largest organ of the human body, serves as a barrier that prevents the
299 penetration of particulate matter. However, there is currently a lack of research on the accumulation
300 and transfer of MNPs on the skin. Alvarez-Roman et al. [105] observed that PS microspheres (20
301 and 200 nm) preferentially accumulate in the follicular openings of porcine skin and increase over
302 time. Whereas the mechanism by which these NPs penetrate the skin barrier remains unclear. Based
303 on previous advances in nanoparticle research, NPs have the potential pathways to penetrate the
304 skin barrier [106, 107]. Currently, there are three pathways by which NPs are transferred from the
305 outer skin to the body: i) via cellular bypass (<1–4 nm); ii) via sweat glands and hair follicles (4–20
306 nm) and iii) damaged skin (21–45 nm) [106]. Indeed, when the skin is severely damaged, there is a
307 possibility that larger-sized NPs can penetrate through.

308 **3.4. MNPs accumulation in organs**

309 After crossing the intestinal barrier and the air-blood barrier, MNPs enter the circulation system.

310 The largest blood vessel in the human body, the aorta, has a diameter of about 25,000 μm and the
311 smallest capillary is about 8 μm [108], which allows convenient transfer of different sizes of MNPs
312 through the bloodstream circulation in the human body and eventually accumulation in organs,
313 tissues and body fluids (Table 2). Researchers detected the presence of PET and PC-type plastics in
314 human blood for the first time [32], although their size was not determined. More investigations are
315 needed to reveal the kinetics of MNPs in blood. Recently, MPs also have been found in human
316 thrombosis ($\sim 5 \mu\text{m}$), the liver (4–30 μm) and even the placenta (5–10 μm) [33, 35, 36], by Raman
317 or infrared spectroscopy. In the future, it is necessary to observe MNPs *in vivo* by labeling them
318 with radioisotopes or upconversion fluorescence, and *in situ* image their location using positron
319 emission computed tomography or photoacoustic imaging techniques.

320 **4. Potential effects of MNPs on human organ systems**

321 The potential impact of MNPs on health is a major concern. The human body mainly consists
322 of nine organ systems, namely the digestive, respiratory, circulatory, reproductive, nervous, immune,
323 endocrine, urinary, and locomotor systems, whose functional balances are required for human well-
324 being. In this paper, the effects of MNPs on these nine organ systems are summarized through
325 knowledge derived from *in vivo* and *in vitro* toxicological studies (Fig. 2).

326 **4.1. Digestive system**

327 The digestive system plays a vital role in breaking down food, absorbing nutrients, and
328 eliminating waste [109]. However, MNPs might have adverse effects on the intestinal tract. MNPs
329 can potentially impact nutrient absorption in the human intestine, disrupt intestinal homeostasis, and
330 ultimately lead to intestinal diseases [110-117].

331 Preliminary experiments have shown that MNPs inhibit lipid digestion and reduce the
332 absorption of vitamin D3 [110, 111], causing nutritional imbalances. The main reason is that MNPs
333 can agglomerate nutrients and reduce their bioavailability or affect the activity of the corresponding
334 enzymes. Additionally, fibrous MPs featured honeycomb-like pores that competitively absorb

335 nutrients [112].

336 A stable intestinal microbiota is essential for human health. MNPs altered the human intestinal
337 microbiota and caused an imbalance in intestinal microecology. *In vivo* exposure experiments in
338 model animals showed that MPs alter bacterial abundance in the intestine of mice, feeding
339 polyethylene (PE) MPs showed significant increased abundances in *Staphylococcus* alongside with
340 a decrease in *Parabacteroides* [113], and feeding polystyrene (PS) MPs decreased *Actinobacteria*
341 abundance [114]. The concentration of MPs also affected the intestinal microbiota, and a high
342 concentrations of PE MPs (600 µg/day) increased intestinal microbial species, bacterial abundance,
343 and flora diversity in mice [113]. Considering the possible access of environmental MNPs that carry
344 microorganisms and even pathogenic bacteria to the human digestive system, their impacts on the
345 stabilization of the intestinal flora deserve carefully examination.

346 MNPs negatively affect human intestinal cells. In human colonic epithelial cells CCD841CoN
347 and small intestinal epithelial cells HIEC-6, 0.1 µm PS microspheres caused cellular oxidative stress
348 and 5 µm PS exposure resulted in higher levels of mitochondrial depolarization [115]. Therefore,
349 MNPs exposure in the intestine causes intestinal barrier dysfunction, metabolic disorders, immune
350 response, inflammation, and ultimately to the development of related diseases [113-117].

351 Risks from co-interactions of MNPs and other contaminants such as heavy metals also should
352 be cautiously considered. Once these contaminants have entered the human body through MNPs as
353 the carrier, their release could greatly impair human health. In an *in vitro* human digestive model,
354 both lead (Pb) and chromium (Cr) could be desorbed from MPs into simulated gastric and intestinal
355 fluids. This is indicative of increased risk of the metals to human health [118, 119]. On the other
356 hand, no significant desorption of benzophenone-3 from MNPs occurred in the simulated human
357 gastrointestinal fluid [120]. Desorption behaviors of pollutants from MNPs in the human
358 gastrointestinal system should be differential, based on the type/size of MNPs, as well as pH and
359 the presence of surfactants in the surrounding intestinal environment.

360 **4.2. Respiratory system**

361 MPs have been detected in both the upper respiratory tract (sputum, nasal cavity) [88] and
362 lower respiratory tract (alveoli, lung tissue) [87, 121] of humans, which raises concerns about their
363 potential health effects on the respiratory system. Although there is still no direct link between
364 MNPs and human respiratory disease, recent research suggests that MNPs may alter endogenous
365 surfactants of human lungs, impair lung cells, and increase their susceptibility to lung disorders such
366 as pulmonary fibrosis, pulmonary frosted glass nodules, and asthma [122-127].

367 Lung surfactants play an important role in reducing alveolar surface tension and preventing
368 invasion by exogenous particles [122]. Researchers discovered an abundance of 9.18 particles/100
369 mL in alveolar lavage fluid, 97.06% of which were fibers [87]. Shi et al. [123] found that MPs
370 modify the phase behavior, surface tension, and membrane structure of simulated lung surfactants,
371 as well as increase the amount of reactive oxygen species (ROS) in lung surfactants by *in vitro*
372 simulations. MNPs were more accessible to lung cells by altering the composition of the pulmonary
373 surfactants, and ROS damaged DNA and caused lung damage [123]. The toxicity of MPs to human
374 lung cells could be correlated to the concentration and size of MPs [124, 125]. Low doses of PS
375 particles ($10 \mu\text{g}/\text{cm}^2$) cause cytotoxic, inflammatory effects in lung epithelial cells (BEAS-2B) and
376 disrupt lung barrier function, while high concentrations ($1,000 \mu\text{g}/\text{cm}^2$) increase the risk of
377 occurrence of chronic obstructive pulmonary disease [125]. The smaller sized MNPs are more toxic
378 to human lung cells, which could be attributed to the higher bioactivity and greater intracellular
379 accumulation of smaller NPs [124].

380 MNPs might be able to cause lung diseases. In mice, $5 \mu\text{m}$ PS MPs were found to persist in
381 lungs, initiated oxidative stress and chronically damaged epithelial tissues, elicited inflammation
382 and consequently activated the Wnt/-catenin signaling that led to lung fibrosis. In addition, inhaled
383 tire wear plastic ($<1 \mu\text{m}$) induced pulmonary fibrosis injury [126]. Moreover, fibrous MPs may be
384 associated with the formation of ground glass nodules in the lung. By comparison with human lung
385 tumors and normal tissue, fibrous MPs were more frequently detected in tumor tissues (58%) than
386 in normal tissues (42%). In people more exposed to MPs in their living or working environment,
387 fibrous MPs were detected in 72% of tumor tissues [127]. To date, the toxicity of MNPs on the

388 respiratory system is not well understood and requires further investigations.

389 4.3. Circulatory system

390 The circulatory system supplies oxygen and nutrients to the various tissues in the body and
391 removes waste products. A recent study has identified the presence of PET, PS, PE and poly (methyl
392 methacrylate) (PMMA) plastics (>700 nm) in the blood of 22 healthy individuals, with an average
393 concentration of 1.6 µg/mL of MNPs [32]. Moreover, MNPs have been identified in human
394 thrombus [128], raising concerns about their potential impact on the human circulatory system.
395 Current evidence suggests that MNPs may be harmful to red blood cells and could potentially affect
396 angiogenesis and platelet function, even leading to thrombosis in humans [129-133].

397 Once entering the circulation, MNPs interact with different components of the blood such as
398 plasma proteins, red blood cells, platelets, and peripheral blood lymphocytes. On the one hand,
399 MNPs absorb plasma proteins to form a multilayer corona on the exterior, resulting in an
400 aggregation effect [129]. On the other hand, MNPs adsorb to the surface of blood erythrocytes, and
401 certain NPs (amino-modified) induce erythrocyte hemolysis [130]. Particulate matter also causes
402 the aggregation and activation of platelets and ultimately the formation of blood thrombosis [131].
403 In addition, MNPs cause cytotoxicity and genotoxicity in human peripheral blood lymphocytes
404 [132]. Moreover, PS MPs reduce the biological activity of endothelial cells, which in turn inhibits
405 angiogenic and wound-healing signaling pathways, thus impacting the development of new blood
406 vessels and wound healing [133]. When blood vessels are injured, endothelial cells promote
407 coagulation and thrombosis by synthesizing and secreting a variety of coagulation-related molecules.
408 These effects are also related to the particle size, shape, and surface charge of MNPs.

409 Current research on the effects of MNPs on the human circulatory system is still limited, and
410 there are several research deficiencies to be addressed. Firstly, most studies have been conducted *in*
411 *vitro*, and there is a lack of *in vivo* studies that can provide more conclusive evidence. Moreover,
412 most studies have focused on the acute effects of MNPs, while chronic exposure studies are needed
413 to understand the long-term effects of MNPs on the circulatory system. Another research deficiency

414 is the lack of standardized protocols for such studies. There is a need for standardized methods for
415 the characterization and quantification of MNPs in blood samples to facilitate comparison between
416 studies. In addition, there is a need for standardized protocols for assessing the effects of MNPs on
417 blood components, including red blood cells, platelets, and peripheral blood lymphocytes.

418 **4.4. Reproductive system**

419 Researchers have recently paid increasing attention to the potential impact of MNPs on the
420 human reproductive system since MPs were discovered in the human placenta [36]. One of the
421 concerns is the potential threat to future generations posed by MNP effects on reproductive health.
422 *In vivo* animal research has demonstrated that MNPs can cause reproductive toxicity and may also
423 have health effects on the offspring [134-139].

424 Studies on mice and rats have shown that MNPs can cause reproductive toxicity in both males
425 and females [134-136]. PS particle exposure at high levels (30 mg/kg body weight) produced
426 ovarian inflammation and decreased oocyte quality in mice [135]. PS particles similarly induced
427 testicular inflammation, decreased sperm quality, and damaged the blood-testis barrier in mice [134].
428 In addition, the reproductive system of female rats is more susceptible to MNPs than that of males
429 [136]. Moreover, Deng et al. [137] demonstrated that exposure to MNPs at a concentration of 50
430 mg/kg of food also influenced the testicular and sperm quality of mice. The underlying mechanisms
431 behind the reproductive toxicity of MNPs are not yet fully understood, but inflammation and lipid
432 metabolic abnormalities may play a significant role [137]. Future research could focus on
433 identifying the specific pathways through which MNPs exert their effects on reproductive health,
434 such as changes in gene expression or disruption of hormonal signaling.

435 To further investigate the effects of MNPs on mouse offspring, Deng et al. [137] found that
436 prolonged exposure of male mice to MNPs decreased body weight and liver mass in the offspring,
437 as well as causing disorders of lipid metabolism. In addition, prolonged maternal exposure to MNPs
438 can cause impaired energy metabolism in the offspring [138]. Recent research detected significantly
439 higher MPs in the placentas of pregnant women with intrauterine growth restriction (302

440 particles/13 placentas) than in normal placentas (6 particles/13 placentas) [139]. As mentioned
441 earlier, MNPs have been shown to have transgenerational effects on reproductive health in animal
442 models. Future research could investigate whether these effects are also present in humans, and
443 whether they are passed down through multiple generations.

444 **4.5. Nervous system**

445 The nervous system is a complex network of neurons that regulates the body's physiological
446 activities [140, 141]. However, there is a paucity of research on the effects of MNPs on the human
447 nervous system. Currently, *in vivo* animal tests have demonstrated that 2 μm PS particles can cross
448 the blood-brain barrier and aggregate in the brain of mice [142]. Qi et al. [143] also discovered
449 exogenous fine particles (such as malayaite and anatase TiO_2) in human cerebrospinal fluids, but no
450 micron-level particles have been identified in the human brain. This suggests that NPs have likely
451 permeated the human brain.

452 Lee et al. [142] further found that MPs affected learning and memory in the brains of mice
453 continuously fed with 2 μm of PS MPs (0.016 mg/g) for eight weeks. This may be mainly due to
454 the fact that PS particles entering the brain cause neuroinflammation in the hippocampus, which in
455 turn alters genes and proteins that contribute to synaptic plasticity [142]. In addition, Wang et al.
456 [144] also found that PS particles (5 μm) induced oxidative stress and reduced acetylcholine levels
457 in mice, resulting in learning and memory impairment. The neurotoxicity of MPs was also
458 dependent on dose, size, composition, and shape [144].

459 Based on current research advances, future *in vivo* and epidemiological research is needed to
460 investigate the potential long-term effects of long-term exposure to MNPs on the human nervous
461 system, including cognitive function and behavior. Additionally, there is a need to explore the effects
462 of MNPs on neural networks and specialized neurons in the human brain by examining changes in
463 neurotransmitter levels, gene expression, and synaptic plasticity following exposure to MNPs, and
464 to study the effects of MNPs on specific populations, such as children, the elderly and individuals
465 with pre-existing neurological disorders. This will help to identify potential vulnerabilities and

466 inform targeted interventions to protect these populations.

467 **4.6. Immune system**

468 The immune system is a network of lymphoid organs, tissues, cells, humoral substances, and
469 cytokines that work together to defend the body [145]. An important function of the immune system
470 is to eliminate invading bacteria, foreign cells, macromolecular compounds (antigens), and
471 extraneous particles. MNPs trigger a local or systemic immunological response when entering an
472 organism, and some MNPs generate a protein corona on their surface that enables them to escape
473 the immune system [129]. Experiments on animals or cells have shown that MNPs can lead to
474 increased secretion of pro-inflammatory cytokines, disrupting immune homeostasis and ultimately
475 leading to immune system disorders such as autoimmune diseases [146-152].

476 Secretion of pro-inflammatory cytokines is essential for maintaining homeostasis of the
477 immune system. In *in vitro* human peripheral blood mononuclear cell experiments, Han et al. found
478 that both acrylonitril-butadiene-styrene (ABS) and polyvinylchloride (PVC) particles induced the
479 release of interleukin 6 (IL-6) and tumor necrosis factor- α (TNF- α) and that the particle size and
480 concentration of plastic particles affected the release of IL-6 and TNF- α [147]. Larger PVC (75–
481 200 μm) tended to induce the release of IL-6 and TNF- α ; And smaller ABS (25–75 μm) particles
482 resulted in the elevated release of IL-6 at higher concentrations (1,000 $\mu\text{g}/\text{mL}$). Conversely, larger
483 ABS (75–200 μm) particles showed a tendency to induce the release of TNF- α across all
484 concentrations (10–1,000 $\mu\text{g}/\text{mL}$) [147]. In addition, mice were exposed to PE particles through the
485 diet and the PE particles were found to induce an intestinal immune response. This resulted in
486 increased levels of interleukin-1 α (IL-1 α) and decreased levels of interleukin 2 (IL-2) [113].
487 Moreover, PS particles cause a maternal-fetal immunological imbalance in mice, which might
488 ultimately result in abortion due to reduced immune cells and the proportion of macrophages [148].
489 An immune system overreacting to MNPs can lead to massive inflammation, resulting in an
490 imbalance in the homeostasis of the immune response.

491 Autoimmune diseases are a group of diseases in which an immune response to an autoantigen

492 leads to damage or dysfunction of the tissues and organs. In addition to genetic factors, autoimmune
493 diseases can be triggered by environmental factors [149]. Numerous studies have demonstrated that
494 air pollution might exacerbate autoimmune disorders. Particularly, ambient fine particulate matter
495 may raise the incidence of systemic lupus erythematosus [150], type 1 diabetes [151], and
496 rheumatoid arthritis [152]. Similarly, environmental MNPs have a strong propensity to induce
497 autoimmune disorders.

498 The immune system is present in various organs throughout the body, including the spleen,
499 lymph nodes, and bone marrow, among others. Future research should investigate the impact of
500 MNP exposure on immune system function in different organs and even overall immune system
501 health. Research is also needed to investigate the effects of MNP exposure on different immune cell
502 populations, including T cells, B cells, macrophages, and dendritic cells.

503 **4.7. Endocrine system**

504 The endocrine system is responsible for regulating the normal physiological activities of the
505 body through hormones. Despite limited toxicity to the endocrine system, MNPs can carry and
506 desorb some endocrine-disrupting chemicals (EDCs), such as bisphenol A, phthalates, or steroid
507 hormones [26, 153]. There is growing evidence from laboratory animal studies and epidemiological
508 studies that EDCs can interfere with the development of the endocrine system and affect the function
509 of organs that respond to hormonal signals [153], leading to a variety of health problems such as
510 reduced sperm quality and sex hormone concentrations, effects on child development, type 2
511 diabetes, obesity, etc [154, 155]. Furthermore, Deng et al. [156] showed that the presence of MNPs
512 significantly increased the absorption of EDCs in the intestine and increased their reproductive
513 toxicity. It is therefore necessary to focus on the interaction between MNPs and EDCs in organisms
514 and to further investigate their combined toxicity to organisms. In addition, other endocrine
515 disruptors such as polychlorinated biphenyls (PCBs) and dioxins are also present in the environment
516 and can enter the body through adsorption on the surface of MNPs, and their release in the body and
517 combined toxicity with MNPs require more attention.

518 4.8. Urinary system

519 The urinary system is the main metabolic pathway of the body and maintains stability within
520 the organism. Unquestionably, MNPs can also penetrate the urinary system and harm the kidneys
521 and bladder. At the cellular level, exposure of human embryonic kidney cells (HEK 293) to PS
522 particles drastically reduces cell proliferation and causes cellular oxidative stress [157]. In addition,
523 PS particles cause mitochondrial dysfunction, endoplasmic reticulum stress, inflammation and
524 autophagy in kidney cells [158]. At the organ level, PS particles (50–400 μm) can accumulate in the
525 kidney, with 600 nm PS particles aggregating while 4 μm PS particles appearing as single particles
526 [159]. MNPs also cause significant kidney quality decrease, histopathological lesions, kidney
527 inflammation, and endoplasmic reticulum stress [158, 159]. In addition, PS particles produce
528 bladder epithelial necrosis and inflammation, with 1–10 μm particles causing the most severe
529 necrosis and 50–100 μm particles causing the most severe inflammatory damage [160].

530 Animal studies have shown that MNPs (100 nm, 3 μm) are excreted in mouse urine [161], and
531 recent studies have shown that MPs are also present in human urine [28]. Pironti et al. detected
532 seven irregular MPs with particle sizes of approximately 4–15 μm in urine samples from six
533 individuals, the main types being PP, PE, polyvinyl acetate, and PVC [28]. Based on the
534 aforementioned studies, future research needs to focus on improving the detection methods for the
535 concentration and particle size range of MNPs in human urine to accurately assess the glomerular
536 filtration rate. Furthermore, future studies should investigate the potential effects of MNP exposure
537 on urinary protein filtration and reabsorption.

538 4.9. Locomotor system

539 MNPs have been shown to inhibit the mobility of fish, soil animals, and birds [162-164], but
540 their effect on the human locomotor system is negligible. However, individuals who use prostheses
541 need to be aware that wear and tear can produce MNPs that may cause inflammation and possible
542 rejection, thereby affecting mobility [165]. MNPs may also affect movement by influencing the
543 central nervous system. For example, one study found that feeding mice food containing MPs

544 resulted in shorter walking distances and slower locomotion [166].

545 **5. Future research recommendations**

546 Based on the above discussion, research on the effects of MNPs on mammalian and, in
547 particular, human health is still in its early stages. There are significant gaps regarding the
548 quantification of the concentrations of MNPs in different foods, the intake of MNPs by different
549 routes of exposure in humans, the absorption and transfer of MNPs in the human body, and the
550 mechanisms of the health effects of MNPs on humans after ingestion. Therefore, systematic and in-
551 depth studies on the effects of MNPs on human health are needed. Recommendations for future
552 research are as follows.

553 i. Standardize MNPs detection methods and establish quality control and quality assurance
554 systems to avoid contamination and facilitate comparison between studies. Based on the nature of
555 MNPs, a standard formula for converting MNPs from abundance to mass concentration needs to be
556 established, which allows for a more realistic and comparable assessment of daily human exposure.

557 ii. Develop *in vitro* models that simulate the complexity of human tissues and organs to better
558 understand the accumulation and transfer of MNP in the human body. There is a further need to
559 develop innovative techniques for characterizing and studying MNPs, including advanced imaging
560 techniques and novel analytical tools for better *in situ* imaging and characterization.

561 iii. Standardize *in vitro* cellular and model animal experiments for dose-response studies of
562 MNPs. Evaluate and compare the toxicity and mechanism of action of different types and particle
563 sizes of MNPs. And conduct long-term epidemiological studies to assess the chronic effects of
564 MNPs on human health. Particularly vulnerable populations, including pregnant women, children,
565 and the elderly, may be more susceptible to the toxic effects of MNPs.

566 iv. Based on the one health framework, the issue of MNPs requires interdisciplinary
567 collaboration and scientific and technological innovation [162]. There is a need to strengthen
568 communication and cooperation between professionals in different fields, explore new research

569 methods and technologies, and promote the solution to MNPs problems.

570 **Author contributions**

571 Y.D.F.: conceptualization, investigation, writing–original draft, writing–original revise. C.T.:
572 conceptualization, investigation, Writing–original draft, supervision, project administration,
573 writing– review & editing. R.J.L., D.W., J.Y.: writing–review & editing. Y.K.X., W.J.G.M.P.:
574 supervision, writing–review & editing. Y.M.L.: conceptualization, supervision, writing–review &
575 editing.

576 **Declaration of competing interests**

577 The authors declare that they have no conflicts of interest.

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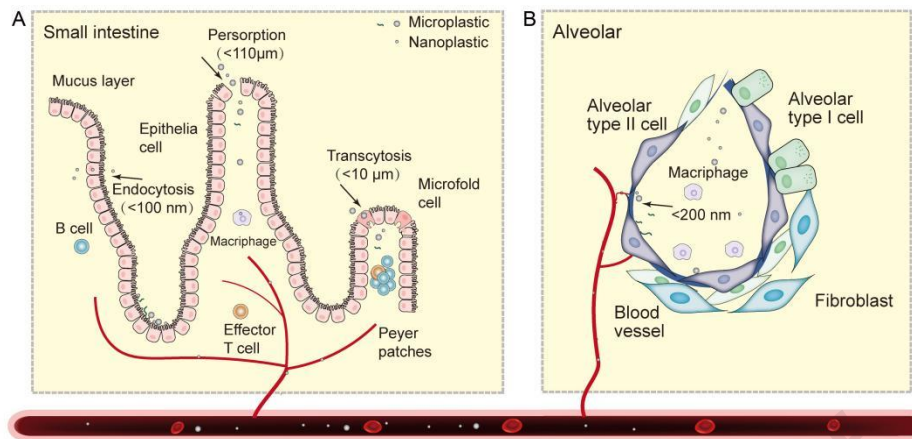
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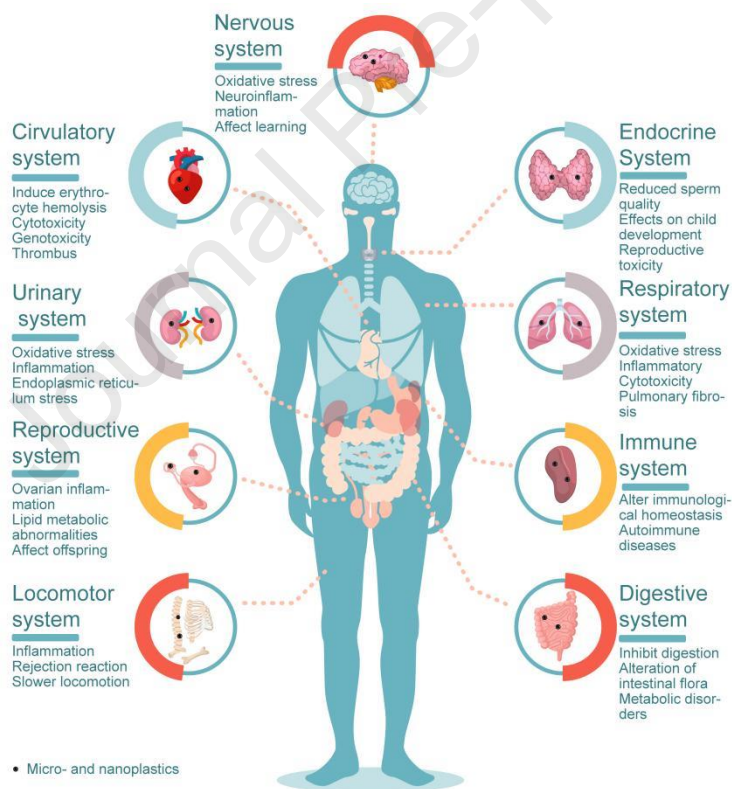
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1072 **Figure 1. The possible absorption, transfer and accumulation mechanisms of micro- and nanoplastics in**
 1073 **human intestines (A) and lungs (B).**



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1075 **Figure 2. Potential health risks of micro- and nano-plastics to nine human organ systems.**

Table 1. Presence of micro- and nano-plastics in the daily human diets.

Species	Location	Abundance	Size (μm)	Type	Shape	Detection method	Reference
Skipjack Tuna (<i>Euthynnus affinis</i>)	Southern Coast of Java, Indonesia	4 particles/fish	500–5,000	/	Filament (84%), angular (11%),	Stereomicroscope	[167]
Deep-sea fish	South China Sea	Stomachs: 1.53±1.08 particles/g intestines: 4.82±4.74 particles/g	0–1,000 (68.9%–76.7%)	/	Film, fiber	Optical microscope	[168]
Oysters	South Australia	0.09±0.01 particles/g wet weight	/	LDPE, PE	Fiber (61.8%), fragment (37.7%),	FTIR	[169]
Mussel (<i>Perna Viridis</i>)	Hong Kong	0.21–1.83 particles/g wet weight	40–1,000	PP (56%), PE (25%), PET (10%)	Fragment, fiber	Raman	[51]
Brown shrimp (<i>Metapenaeus monoceros</i>)	Bangladesh coast	3.40±1.23 particles/g digestive tract	1,000–5,000 (40%) 500–1,000 (17%)	PA, rayon	Fiber (57%), particle (29%), fragment (14%)	μ -FTIR	[170]
Tiger shrimp (<i>Penaeus monodon</i>)	Bangladesh coast	3.87±1.05 particles /g digestive tract	1,000–5,000 (70%) 500–1,000 (27%)	PA, rayon	Fiber (32%), particle (16%), fragment (26%)	μ -FTIR	[170]
Whiteleg shrimp (<i>Litopenaeus vannamei</i>)	Malaysia	20.8±3.57 particles /g wet weight	/	/	Film (93%–97%)	Microscope	[50]
Argentine red shrimp (<i>Pleoticus</i>)	Argentina Southwest Atlantic,	7,050±4,178 particles/g wet weight	/	/	Sphere (70%)	Microscope	[50]

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Dried fish	Taiwan, Thailand, Japan , China, South Korea, Vietnam and Sri Lanka	0–0.56 particles/g (dried fish)	/	PE (35%), PET (26%), PS (18%)	Fiber, fragment, film	μ-Raman, FTIR	[11]
Tap water	China	440±275 particles/L	1–50 (31.25%–100%) 50–100 (1.47%–31.25%) 100–300 (1.72%–31.25%)	PE (26.8%), PP (24.4%), PE+PP (22.0%)	Fragment: 53.85%– 100%, fiber: 1.18%– 30.77%. sphere: 2.27%– 36.36%.	μ-Raman	[171]
Tap water ^a	Barcelona Metropolitan Area	1 ng/L–9 μg/L	0.7–20	PE, PP		HPLC–HRMS	[172]
Drinking water	Mexico City	18±7 particles/L	100–1,000 (75%)	PTT, EP	Fibers	μ-Raman	[173]
Bottled water	Kermanshah , Iran	8.5±10.2 particles/L	1,280–4,200	PET, PS, PP	fragment (93 %), fiber (7%)	FTIR, Raman	[174]
Mineral water							
Bottled water	China	2–23 particles/bottle	25–5,000	Cellulose (71.16%), PET (6.98%), PE (6.05%)	Fiber, fragment	μ-FTIR	[175]
Soft drinks	Mexico	ND–7 particles/L	100–3,000	PA	Fiber	Microscope	[60]
Cold tea	Mexico	1–6 particles/L	100–2,000	PA	Fiber	Microscope	
Beer	Mexico	ND–28 particles/L	100–3,000	PA	Fiber, fragment	Microscope	
Milk	Switzerland; France	2,040–10,040	≥5, <20	PE (31%), PS	/	μ-Raman	[61]

Table salts	Africa	1.68±1.83 particles/kg	>50, <5000	(27%), PES (23%) PVA, PP, PE	fragment, fiber, granule	FTIR	[176]
Table salts	India	115–575 particles/kg	100–200 (37.7%), 200– 500 (31.2%), 500–1,000 (16.2%) >1000 (15%)	PE (78%), PE (19%), PVC (3%)	Fibers (88.5%), film (4.9%), pellet (2.9%)	μ-FTIR	[14]
Sugar	Bangladeshi	343.7±32.08 particles/kg	<300 (64%)	ABS (25%), PVC (18%), PET (15%)	Fiber (38.4%), fragment (28.4%), film (25.2%)	FTIR	[65]

^a mass concentrations. LDPE, low-density polyethylene; PP, polypropylene; EP, epoxy resin; PET, polyethylene terephthalate; PE, polyethylene; PA, polyamide; PES, polyester; PVC, polyvinyl chloride; PVA, polyvinyl acetate; ABS, acrylonitrile butadiene styrene; FTIR, fourier transform infrared; HPLC–HRMS, high performance liquid chromatography- high-resolution mass spectrometry.

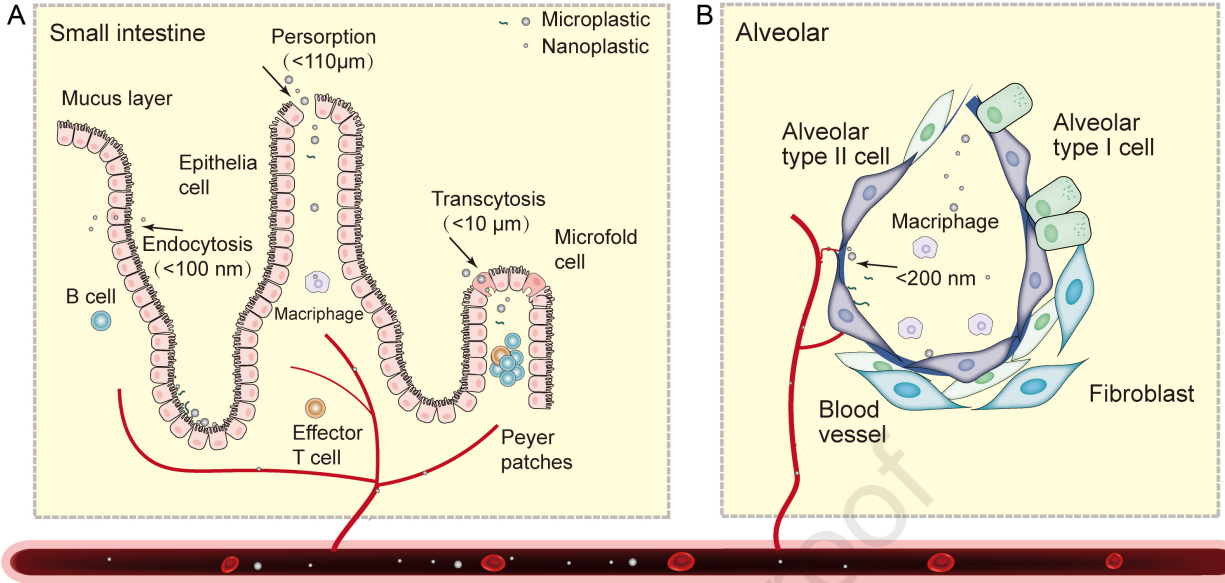
Table 2. Presence of micro- and nano-plastics in human tissues or fluids.

Human body sample	Digestion methods	Detection method	Sample Number	Type	Shape	Abundance	Size (μm)	Reference
Lung	H ₂ O ₂ (30%, v/v)	μ -FTIR, Raman	100	Cotton, rayon, PE	Fiber (>90%)	Tumor tissues: 38 particles/50 samples, normal tissues: 27 particles/50 samples	1,450 \pm 980	[86]
Lung	Enzymatic	Raman	20	PP (35.1%), PE (24.3%), cotton (16.2%)	Fragment (87.5%), fiber (12.5%)	0.56 particles/g of lung tissue	Fragment : 1.60-5.56 fiber: 8.12-16.80	[30]
Lung	30% H ₂ O ₂	μ -FTIR	13	PP (23%), PET (18%), resin (15%)	Fragment (67%), fiber (22%)	1.42 \pm 1.50 particles/g	12–2,475	[121]
Bronchoalveolar lavage fluid	No	μ -FTIR	44	Rayon (40.48%), PE (19.05%), cellulose (16.67%)	Fiber (97.06%)	9.18 \pm 2.45 particles/100 mL	1,730 \pm 150	[87]
Sputum	HNO ₃ , NaOH	FTIR	22	PU, PE, PVC	-	18.75–91.75 particles/10 mL	20–500	[29]
Sputum	30% KOH	Polarized light microscopy	16	Couriers: PC (24.2%), PVC (23.0%); office staff: PVC (39.1%), PA (24.8%)	Couriers: fiber (94.3%), office staff: fiber (83.3%)	Couriers: 26.9–161.5 particles/g Office staff: 0.4–1.4 particles/g	-	[88]
Nasal lavage fluid	30% KOH	FTIR	16	Couriers: PA	Couriers: Fiber	Couriers: 17.6–728.6	-	[88]

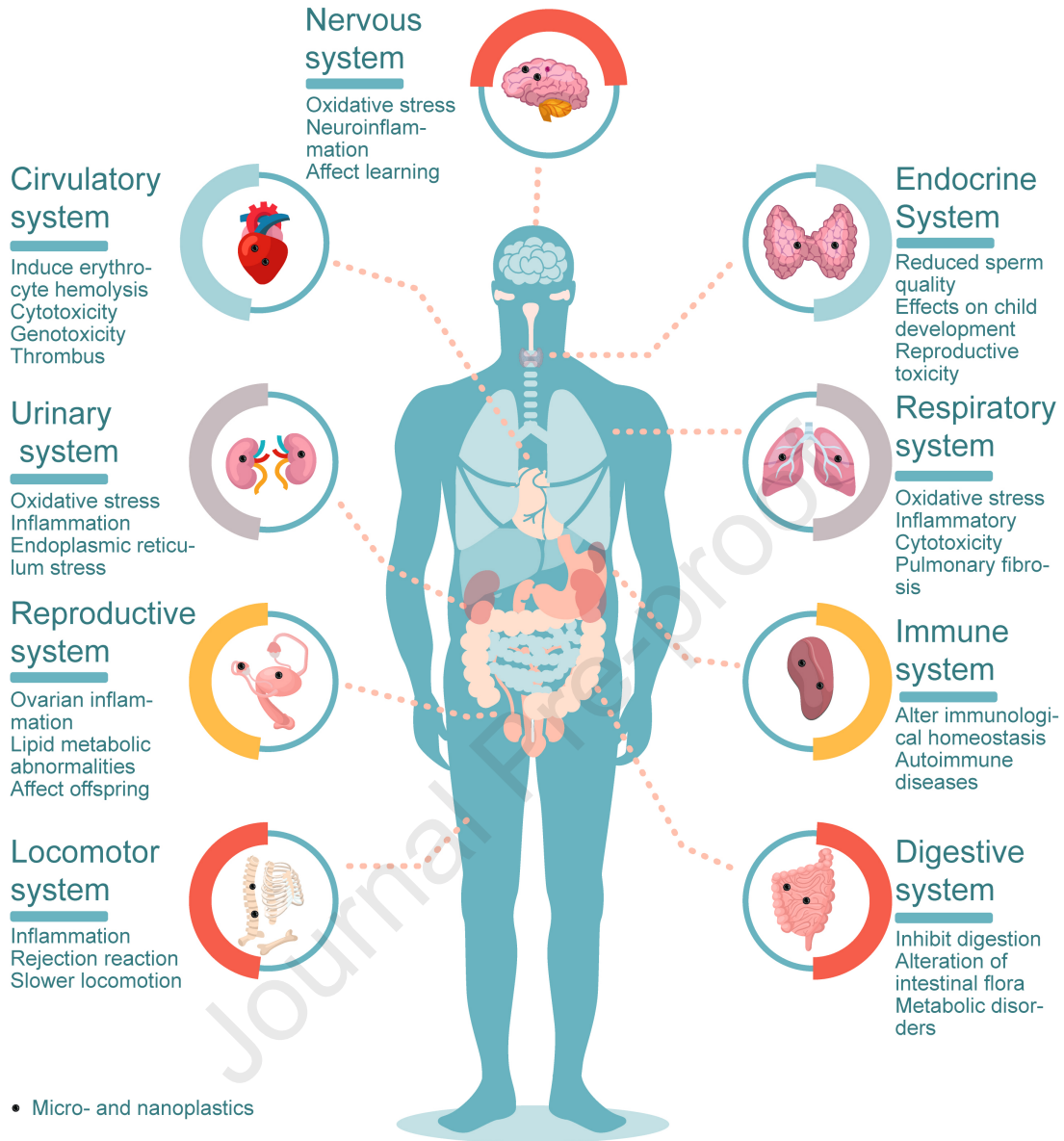
				(25.3%), PE (22.9%); office staff: PVC (41.1%), PA (31.6%)	(83.8%); office staff: fiber (87%)	particles/g; office staff: 0.9–3.3 particles/g		
Human blood ^a	Proteinase K	Py-GC/MS	22	PET, PE	-	1.6 µg/ml	≥0.7	[32]
Thrombi	30%KOH	Raman	26	LDPE	Fragment	1 particle/26 sample	~5	[33]
Liver, spleen, kidney	KOH	Raman	Liver(11), spleen(3), kidney(3)	PS, PVC, PET	-	1.4 particles/g	4–30	[35]
Placenta	10% KOH	Raman	43	PE, PS	Film, fiber, fragment	Normal:6 particles/30 sample IUGR:302 particles/13 sample	Normal:7.3–27.6 IUGR: 2.9–34.5	[139]
Placenta	10% KOH	Raman	6	PP	Fragment	4 particles/6 placentas	~5–10	[36]
Breast milk	10% KOH	Raman	34	PE (38%), PVC (21%), PP (17%)	Fragment	26 particles/34 samples	2–12	[177]
Human colectomy	10% KOH	FTIR	11	PC, PA, PP	Fiber (96.1%),	28.1±15.4 particles/g	800–1,600	[31]
Adult stool ^a	H ₂ O ₂ 30%,	FTIR	26	PET, PP, PS	-	1–36 particles/g	20–800	[178]
Infant stool ^a	KOH	LC–MS/MS	6	PET, PC	-	PET: 5,700–82,000 ng/g PC: 49–2,100 ng/g	-	[98]
Meconium ^a	KOH	LC–MS/MS	3	PET, PC	-	PET: 3,200–12,000 ng/g PC: 110 ng/g	-	
Adult stool		FTIR	8	PP (62.8%), PET (17.0%), PS (11.2%)		20 particles/10g	50–500	[96]

Adult stool ^a	KOH	LC-MS/MS	10	PET, PC	-	PET: <16,000 ng/g PC: 37-620 ng/g	-	[98]
Urine	KOH	Raman	6	PP, PE, PVC, PVA	fragment	-	4-15	[34]

^a mass concentrations. PP, polypropylene; PET, polyethylene terephthalate; PE, polyethylene; PU, polyether urethane; LDPE, low-density polyethylene; PC, polycarbonate; PA, polyamide; PVC, polyvinyl chloride; PVA, polyethylene vinyl acetate; FTIR, Fourier-transform infrared spectroscopy; Py-GC/MS, pyrolysis gas chromatography-mass spectrometry; LC-MS/MS, liquid chromatography-tandem mass spectrometry. IUGR, intrauterine growth restriction.



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Highlights

Human exposure to micro- and nano-plastics (MNPs) via inhalation, ingestion and dermal contact are summarized.

MNPs have an intrinsic capability to escape and to translocate to the circulatory system.

MNPs have the potential to disrupt homeostasis, leading to oxidative stress, cytotoxicity, tissue damage, and systemic dysfunction.

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