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MICRO AND NANOPLASTICS IN TERRESTRIAL MAMMALS: CURRENT KNOWLEDGE AND RESEARCH GAPS

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ABSTRACT

Micro and nano plastics (MNPs), originating from environmental pollution, consumer products and industrial processes, are being detected increasingly across numerous ecosystems and food chains. Their pervasive nature elevates the possibility of human and animal exposure through ingestion, inhalation and dermal contact, underscoring the need for scientific investigations into their presence and effects on "One Health". With a view to consolidating the current state of knowledge, identifying similarity between humans and animals, research gaps and paving the way for evaluating the potential toxicological and health implications of these particles, a crucial systematic literature review has been conducted to study the detection of MNPs in specific mammalian (human and animal) tissues, whilst also examining experimental models assessing their toxicological effects. By synthesizing findings across biomedical and environmental research, the review elucidates the pathways through which these particles enter and accumulate in the body. Furthermore, it highlights the potential health risks posed by chronic exposure, including inflammatory responses, oxidative stress, and tissue damage. However, the current evidence remains insufficient to establish a quantitative balance across exposure routes and body tissues due to the lack of harmonized exposure data, heterogeneity in methodologies, inconsistent reporting, and lack of biological/clearance data. Recognition of this constraint is crucial to a more accurate contextualization of current findings, which is key for the purpose of shaping public health policies and regulatory frameworks to mitigate exposure to microplastics. Given the interdisciplinary nature of the topic, the review bridges diverse fields to create a robust foundation for future research.

1. INTRODUCTION

The presence of microplastics in the environment has caused growing concern at all levels of society, ranging from local and regional to global. These contaminants have been detected in numerous environmental matrices including air (Allen et al., 2019; Beaurepaire et al., 2021; Truong et al., 2021), water (Horton et al., 2017; Altuğ & Erdoğan 2022; Gong et al., 2023; Poli et al., 2024), soil (Huerta Lwanga et al., 2016; Kanteraki et al., 2022), organic amendments (Colombini et al., 2022; Edo et al., 2022; Öling-Wärnå et al., 2023; Porterfield et al., 2023) and the food chain (Huerta Lwanga et al., 2017; Oliveri Conti et al., 2020).

Terrestrial mammals have become increasingly exposed to microplastics through ingestion and subsequent crossing of the digestive tract epithelia, inhalation through the respiratory tract and dermal contact through the cutaneous layer.

Based on dimensions, plastics are broken down into mesoplastics (5-25 mm), microplastics (0.001-5 mm), and nanoplastics (10^{-6}-0.001 mm) (Bandini et al., 2022; EU Commission. 2023; Gigault et al., 2018; Meegoda & Hettiarachchi 2023). Each category is associated with specific characteristics related to environmental fate, uptake, and health risk assessment. Indeed, based on their physical characteristics (particle size, surface chemistry, cell type and biomolecular corona), once meso-, micro- and nano-plastics (MNPs) enter the body by any route, they are able to move, break and establish themselves across a series of organs (Barceló et al., 2023).

Following deposition, accumulation of ample quantities of micro- and nanoplastics throughout a range of tracts could impair functioning of the affected organs. MNPs analysis presents unique challenges for detection and quantification, including particle sizes, diversity in polymer types that require specific detection techniques, and

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the alteration of physical and chemical properties by natural weathering or interference from other substances. The relatively low concentrations of MNPs present in terrestrial, as compared to environmental, matrices necessitate the use of highly sensitive testing methods, added to the potential interference from background contamination. To counter this, approaches such as the Limit of Quantification (LOQ), a contamination adjustment approach used to reliably quantify the lowest concentrations with acceptable precision and accuracy under the required experimental conditions, are applied (Leonard et al., 2024).

Additional variables such as age and gender exposure patterns, are of particular interest as they tend to influence the intake and accumulation of MNPs in organisms (Jenner et al., 2022; Zhu et al., 2024). with specific population groups such as children and the elderly proving potentially more vulnerable to their potential effects. Fetuses start to accumulate MNPs from the mother's blood whilst still in the womb, with their weak detoxification mechanisms potentially resulting in an increase likelihood of exposure (Chen et al., 2023). Likewise, the elderly are rendered more vulnerable due to their reduced immunity and weaker gut barrier and lung epithelia (Fulop et al., 2018). Based on their diverse metabolisms, the impact produced on male and female mammals may differ, thus impinging on the retention and accumulation of MNPs (Björvang & Mamsen 2022; Dominelli et al., 2018; Gade et al., 2021).

Although numerous studies have documented MNP contamination in marine organisms (Cole et al., 2013; Li et al., 2018; Mistri et al., 2022; Moreira-Mendieta et al., 2023; Yin et al., 2022), evidence in terrestrial mammals remains limited and scattered. In this context, a systematic literature review providing for the collection, analysis and comparison of current data relating to the presence of MNPs in human and animal organisms is essential to consolidate the current knowledge on this topic. Accordingly, the present review was undertaken with the aim of: (i) identifying the main sources and exposure pathways of MNPs in mammals; (ii) evaluating the distribution of MNPs across different tissues; and (iii) comparing findings in humans with those from studies on domestic and wild animals, highlighting similarities and differences in bioaccumulation patterns. This comparison may help to determine whether animals can serve as sentinel models for human exposure and to better estimate potential health risks.

Furthermore, the review was intended to help identify any major methodological limitations and research gaps, providing clear directions for future investigations and supporting the development of standardized protocols. The ultimate goal will be to promote a One Health approach that acknowledges the interconnectedness of environmental, animal, and human health in assessing the risks associated with MNP contamination.

2. METHODOLOGY

This systematic review focused on identifying studies that detected MNPs in terrestrial mammals. The search was divided into two parts separating the studies on microplastics (MPs) in humans from other terrestrial mammals. PubMed was used exclusively for the human-focused search as it is powered by MEDLINE, a bibliographic database that contains reliable peer-reviewed articles specialized in biomedicine and health sciences. The search strategy involved combining the terms "microplastic", "human" and 13 target tissues, resulting in the following query: "(Microplastic) AND (human) AND (tissue OR thrombi OR artery OR placenta OR lung OR gut OR blood OR kidney OR brain OR ovary OR breast OR colon OR semen)". On the other hand, PubMed, Web of Science (WOS) and SCOPUS were employed to gather relevant literature on other terrestrial mammals, as both databases provide broad coverage of high-quality peer-reviewed publications. A comprehensive search query was formulated and applied within the field of Title, Abstract and Keywords. The search terms consisted of: "microplastic" OR "nanoplastic" AND common names of 48 animal species spanning 10 of the most common taxonomic orders of terrestrial mammals as seen in Table S1 in supplementary materials.

The search was performed using the 'all fields' option and was limited to original articles published in English. No time restrictions were applied. Review articles, conference proceedings, books, and publications deemed irrelevant or inadequate for data extraction were excluded during the screening process.

Data regarding key findings, sample size, plastics characteristics and origins, as well as laboratory techniques used, were extracted from included articles and recorded in Excel spreadsheets. Following a critical analysis, major trends were observed and discussed narratively, highlighting existing knowledge gaps and challenges in current research. Ethical concerns were considered by ensuring all studies complied with ethical requirements from different institutions concerned.

3. RESULTS AND DISCUSSION

The results of the selection process, including identification, screening, assessment of eligibility and inclusion are illustrated in the PRISMA flow diagram in Figure 1. Specific reasons for exclusion of articles are summarized in Table S2 of the supplementary materials. Following the selection process, we retained a total of 29 papers investigating the presence of plastic particles in the human body and 10 in other mammalian organisms. In addition, 38 studies assessing the effects of various plastic types on various tissues using in vitro models, were incorporated as they provided valuable insights into potential health risks. While the search strategy used through the different databases resulted in an imbalance and could have biased retention, this selection was used so as to maximize the likelihood of retrieving the most relevant studies in humans and other terrestrial mammals. Also, additional searches confirmed that this imbalance reflects the current scarcity of studies. Furthermore, in accordance with PRISMA guidelines for transparency, reproducibility, and scientific rigor, the authors deliberately excluded grey literature from the selection process. Although this inevitably reduced the size of the dataset, it guaranteed the inclusion of high-quality, peer-reviewed, and accessible studies only. This choice enhanced the reliability and compa-

rability of the results, while also underscoring the limited availability of robust peer-reviewed research in this field.

3.1 Micro and Nano plastics in human tissues

The papers reviewed involved participants across a range of age groups (children between 0-15 yrs, adults >18 to 60 years, and the elderly >60 years) and both sexes, as elaborated in Figure 2. Samples from general body tissues were obtained from both male and female individuals, meanwhile studies focused on specific reproductive organs obtained separate samples from each sex as required. Very few studies, however, reported gender analysis and limited

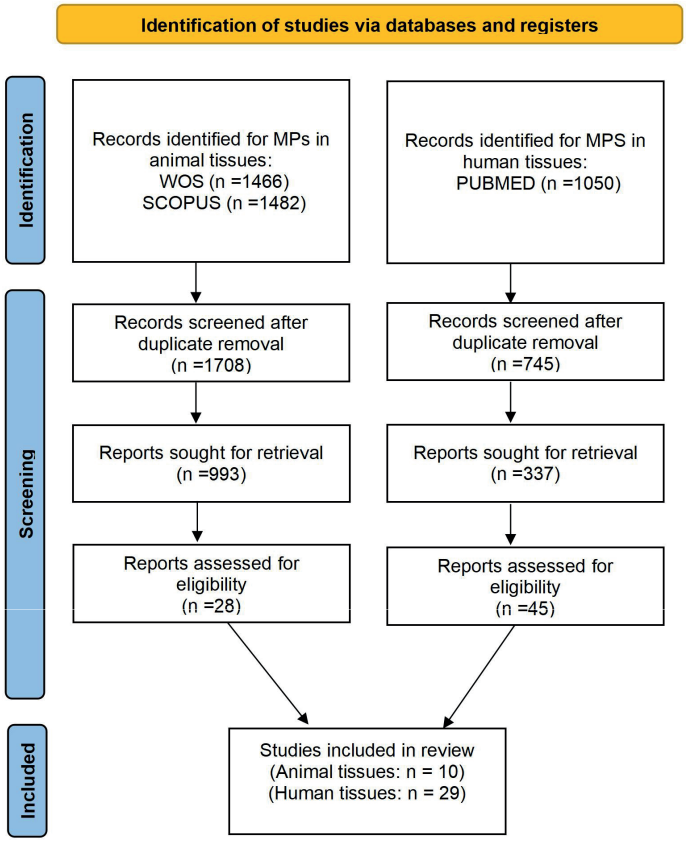

FIGURE 1: PRISMA flow diagram illustrating the study selection process.

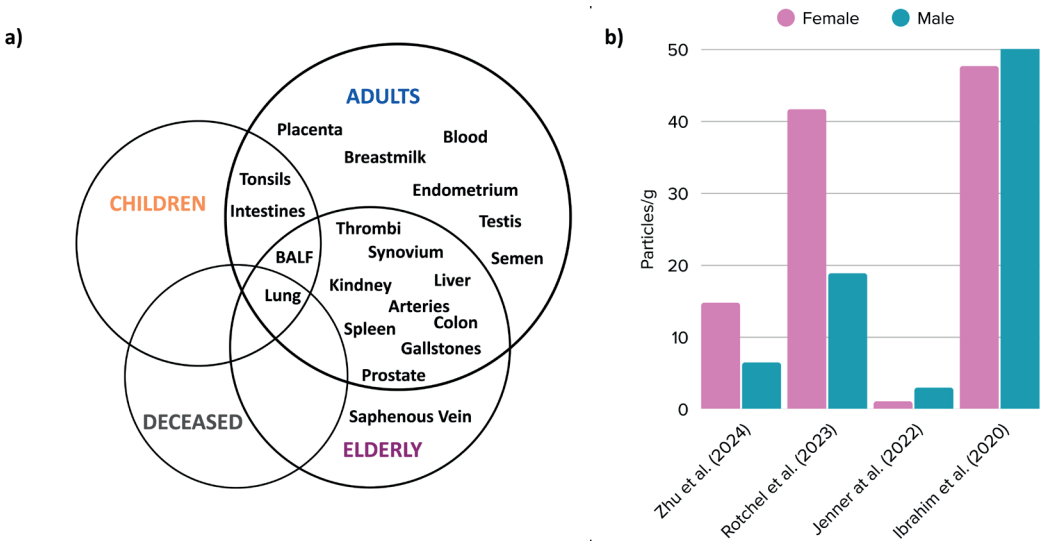

FIGURE 2: Overview of sampled populations and gender-based microplastic abundance comparisons; a) Venn diagram showing the distribution of sampled population groups across studies, with intersections indicating common tissue types analyzed; b) Comparison of some selected studies on general body tissues; lung, tonsil, intestines (Zhu et al. 2024); lung (Jenner et al. 2022); vein (Rotchell et al. 2023) & colon (Ibrahim et al. 2020), highlighting potential gender-related differences in microplastic accumulation.

comparison to concentrations. The small sample size in some studies, constrained by limited control over patient recruitment, coupled with the study of heterogeneous tissues across populations, given the availability in various settings, introduced a risk of bias in the overall assessment of studies and limited age or gender analysis. Thus, highlighting the need for a standardized design in further studies to clarify patterns of MNPs distribution in humans.

In general, samples were collected from both patients with diagnosed pathologies and healthy individuals, as certain studies aimed to investigate the potential associations between microplastic exposure and medical conditions. One study used samples obtained from autopsies and all samples were obtained following written consent and permissions granted by the health infrastructures involved.

MNps have been extensively detected and quantified in several human body tissues embedded in the circulatory, digestive, lymphatic, respiratory, reproductive, and urinary systems. The first study indicative of this contamination in the human body was conducted in Malaysia by Ibrahim et al., (2020) on patients (age range 36-72 years) scheduled for colectomy (Ibrahim et al., 2020). The study aimed at polymer identification and characterization due to the increasingly reported exposure of MNPs through the food chain. Besides, the authors highlighted easy approval and accessibility to samples from routine surgeries performed in patients with colorectal conditions, thereby minimizing the need for invasive procedures.

Based on the selected papers, the results highlighted the following priority by numbers of studies, which reflects the distribution of scientific attention across human organs in the context of MNP detection (Figure 3): placenta (Amereh et al., 2022; Garcia et al., 2024; Liu et al., 2023; Ragusa et al., 2021, 2021; Weingrill et al., 2023; Zhu et al., 2023); lungs (Amato-Lourenço et al., 2021; Jenner et al., 2022; Zhu et al., 2024); bronchioalveolar lavage fluid (BALF) (Baeza-Martínez et al., 2022; Chen et al., 2023), blood (Leslie et al., 2022a; V. L. Leonard et al., 2024); liver, kidney, urine, spleen (Horvatits et al., 2022; Massardo et al., 2024); meconium, infant feces, breast milk (Liu et al., 2023); knee tissues (Z. Li et al., 2024); thrombi (T. Wang et al., 2024; D. Wu et al., 2023); arteries (Liu et al., 2024); saphenous vein (Rotchell et al., 2023); gallstone (Zhang et al., 2024) and intestines (Zhu et al., 2024); other body fluids such as saliva (Abbasi & Turner 2021), urine, and feces (Abbasi & Turner 2021; Liu et al., 2023; Yan et al., 2022) are also being investigated and have been shown to harbor micro- and nanoplastics. However, the latter primarily provides information on contaminants excreted from the body, which is beyond the scope of this review. These were therefore not included in this review.

3.1.1 Abundance of MNPs in human tissues

Typically, the concentration of MNPs in human tissues was reported in units of microplastic particles per gram of tissue (Figure 4), mainly attributed to ingestion and inhalation (La Porta et al., 2023). The digestive system contains

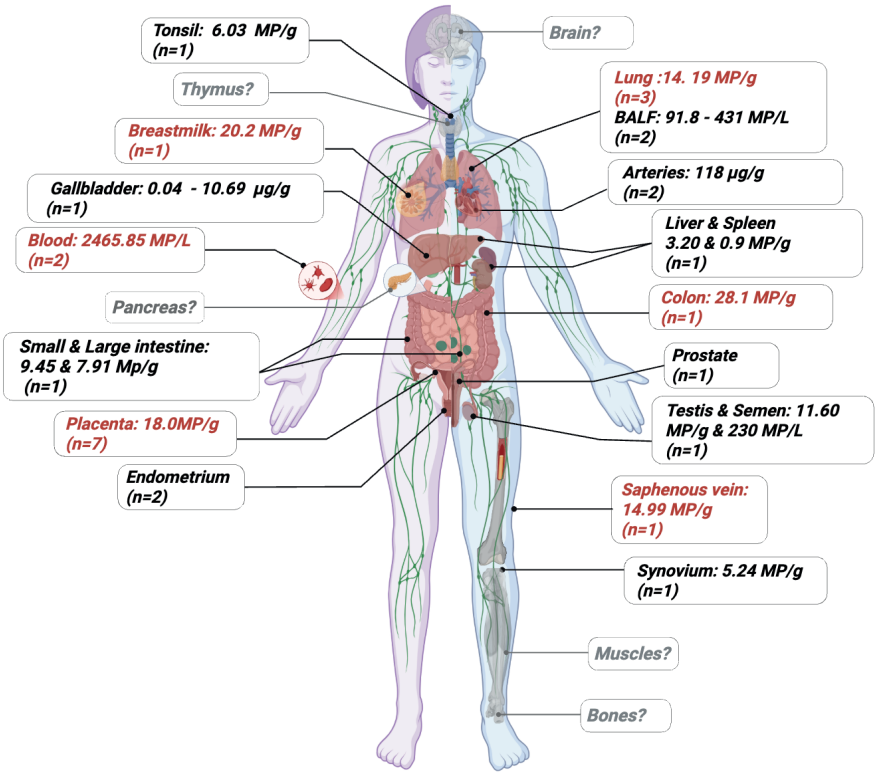

FIGURE 3: Overview of regions assessed for MNPs presence in humans, including specific male and female organs. Analyzed tissues, alongside study counts registered in the reviewed studies are displayed, providing insight into the current research distribution. Tissues highlighted in red indicate the highest concentrations, meanwhile, in grey are currently unexplored pertinent tissues (Created by the authors using BioRender. https://BioRender.com/xs1b5oc).

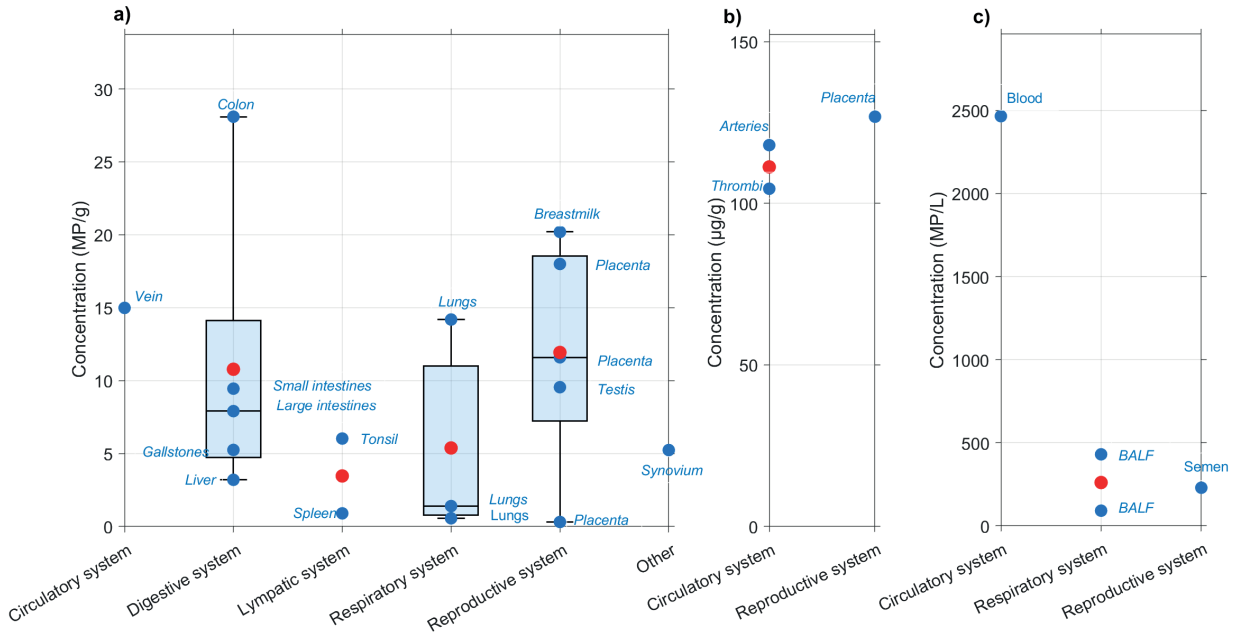

FIGURE 4: Concentration of microplastics across various human body systems. The data illustrate the relative abundance of microplastic polymers using different units of measurement: (a) MNP particles/g; (b) µg/g; (c) MNP particles/L. Each data point represents the outcome of a single study, with the specific organ or tissue labelled adjacent to the corresponding point. For body systems with more than two studies available, the mean value is indicated by a red dot. For systems with three or more studies, a boxplot is included, with the inner black line representing the median concentration.

the colon tissues, from which the most substantial concentration of 28.1 ± 15.4 particles/g was registered. This could be explained by the vital role it plays following the breakdown of large particles alongside food and other ingested compounds through transformation into forms ready for nutrient absorption or compaction of indigestible fraction to feces, which is then transferred to the rectum awaiting expulsion. Smaller concentrations of approx. 9.45 ±13.13 and 7.91 ±7.00 particles/g were recorded in the small and large intestines, respectively (Zhu et al., 2024), 3.2 particles/g in the liver (Horvatits et al., 2022) and 5.25 ± 4.88 particles/g in the gall bladder (Zhang et al., 2024). Despite the use of similar digestion protocols in these studies, filters with smaller pore sizes were used in analysis of the colon and liver (0.45 µm) as compared to those used for the intestines (20 µm), thus a possible justification of differential abundance. Moreover, identification techniques used in the colon-focused study included stereo-spectroscopy, SEM/EDX and µFTIR, meanwhile the latter used LDIR coupled with FTIR for particles. This disparity in methodology coupled with the insufficient number of studies, rendered the comparison challenging, thus highlighting the need for further studies with emphasis on the use of a standard methodology.

The abovementioned study of the digestive system by Zhu et al., (2024) also analyzed tonsil and lung samples on observing discrepancies between loads across age groups and genders. The age group comparison revealed how adults (>18 yrs) featured the highest loads of MNPs compared to infants (0-2 yrs) and children (2-11 yrs), thus establishing a correlation between age and accumulation potential. Moreover, on examining discrepancies according to gender, female samples were reported to be much richer in MNPs compared to males in all tissues, with an average abundance of 14.81 particles/g and 6.47 particles/g, respectively (Figure 4). This finding appears to suggest that in addition to particle properties, clearance mechanisms may also depend on lung physiology and anatomy of the receptor, as females generally tend to have smaller thoracic cavities and narrower respiratory tracts than males, thus featuring a weaker clearance capacity allowing for increased accumulation of microparticles in their lungs (Dominelli et al., 2018). A clinical study conducted in the UK yielded contradictory results as lung samples obtained from males were found to contain an abundance of MNPs, registering 2.09 ± 1.54 particles/g compared to females 0.36 ± 0.50 particles/g. In an attempt to explain this discrepancy, the same physiological differences of clearance capacity were used, thus underscoring the uncertainty and need for standardized analytical techniques and larger sample size to clarify potential sex-related differences regarding accumulation of these particles (Jenner et al., 2022). Across lung compartments, relatively low concentrations of microplastics were quantified (in the upper, mid, and lower parts), with the highest proportion detected in the lower region with 3.12 ± 1.30 MP/g (adjusted to 1.65 ± 0.88 MP/g having subtracted background contamination) compared to 0.80 ± 0.96 MP/g identified within the upper region (adjusted to 0.23 ± 0.28 MP/g) and 0.41 ± 0.37 MP/g within the middle / lingular region (adjusted to 0.33 ± 0.37 MP/g). Moreover, mucociliary clearance in the respiratory tract may cause these particles to be swallowed into the digestive system, thus providing an additional channel allowing en-

try of MNPs into the digestive system (Prata, 2018). High concentrations in the lower regions could favor long-term retention in the lungs, absorption into the bloodstream, or translocation to backup clearance systems such as the lymphatic vessels, all of which are vulnerable to chronic inflammation.

Another notable quantification of MNPs in the human body was recorded by Liu et al., (2023) from the female reproductive/ gynecological system, which encompasses breastmilk (20.2 particles/g) and the placenta (18 particles/g). Earlier reports of MNPs concentration in women's placentas revealed relatively smaller quantities during an extended study of three consecutive intervals by Weingrill, who, per 50g sample, found: 4.1 ± 1.3 MNPs particles in 2006, 7.1 ± 0.9 MNPs in 2013, and 15.5 ± 3.0 MNPs in 2021 (Weingrill et al., 2023), with the more recent data indicating an evident increase over time. In terms of mass concentrations, 126.8 ± 147.5 µg/g were obtained from the placenta (Garcia et al., 2024), while the arteries revealed concentrations of 118.7 µg/g and the thrombi an average concentration of 104.5 µg/g (Liu et al., 2024; T. Wang et al., 2024). These values are relatively comparable and pinpoint the movement of MNPs in circulation. This finding is particularly intriguing, suggesting the potential ability of MNPs to cross the highly vascularized placenta during blood exchange between the mother and fetus.

A recent analysis undertaken by Leonard et al., (2024) studied blood samples obtained from 20 healthy volunteers, recording an average concentration of 2465.85 particles/L. Eight of the samples contained MNPs that met LOQ criteria, obtained following subtraction of instrument sensitivity and background contamination. This suggests significant bioaccumulation in the blood, particularly as this value was five times greater than the 431 particles/L recorded in bronchoalveolar fluids (Chen et al., 2023). The former study presented an equivalence of concentrations in mass per volume with a range of 1.84-4.65 µg/mL, therefore an apparently slightly lower level than that obtained two years previously by Leslie et al., (2022), who registered a maximum of 7.1 µg/mL concentrations in blood samples obtained in the Netherlands (Leslie et al., 2022a). However, when applying LOQ to the latter, the majority of concentrations were found to be <1 µg/mL. On this occasion, no gender and age-based analyses were performed as personal information relating to volunteers had not been disclosed.

3.1.2 Range of MNP sizes found in human tissues and characterization of polymer types

Across the studies considered, the size distribution of identified particles was solely in the micro-range with dimensions 1µm to larger 9 mm fibers in bronchoalveolar lavage fluid (Baeza-Martínez et al., 2022; Chen et al., 2023). Nonetheless, most particles fell in the range of 1-500 µm as seen in samples from the lymphatic system between 4 and 471.8 µm (Horvatits et al., 2022; Zhu et al., 2024), the reproductive system with particles in the range of 2 and 500 µm (Amereh et al., 2022; Demirelli et al., 2024; Ragusa et al., 2022), and urinary system between 1 and 30 µm (Massardo et al., 2024) (Figure 5). The presence of systemic and more specialized biological barriers could influence the predominance of smaller sizes (ranging between tens of micrometers or below) in the tissues of the reproductive and urinary system, as compared to the systems located behind just one epithelial or endothelial layer, such as the circulatory and lymphatic system. Nanometric particle

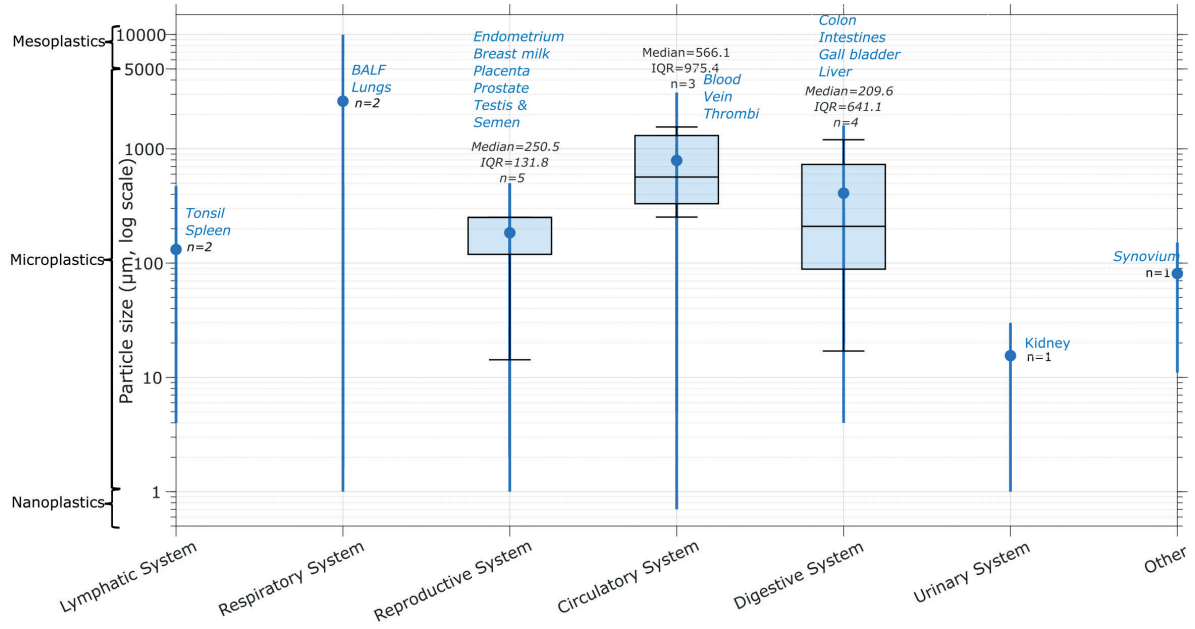

FIGURE 5: Size ranges of microplastics detected across different systems in the human body. Blue vertical lines indicate the range of particle sizes reported, while blue dots represent the mean values for each body system. For systems represented by three or more studies, a boxplot is included, with the inner black line representing the median concentration and the whiskers showing the full spread of the tissue means. The section for the reproductive system contains distinctive tissues from males and females (BALF, bronchoalveolar lavage fluids).

lengths were recorded in the blood (Leslie et al., 2022), yet particle lengths were also recorded in the millimetric range (Leonard et al., 2024) which confirms that the transport function of blood allows a broader size spectrum as compared to other tissues in the same system, such as the arteries and veins, which perform a more size-dependent retention. Nonetheless, the respiratory system, including lungs, BALF, and the colon in the digestive system, which have little or no protective interfaces, facilitates contact between MNPs in sizes of hundreds to thousands of µm through ingestion and inhalation. The predominance of larger particles in these organs reflects their role as primary entry routes, whereas smaller fragments and nanoplastics tend to pass epithelial barriers and accumulate in deeper tissues. These findings demonstrate that particle size distributions across organs are not random but are shaped by the combined effects of exposure route, barrier selectivity, and systemic transport dynamics.

Notwithstanding, the limited quantitative datasets and heterogeneous analytical protocols remained a major constraint, especially in nanoparticle detection, as filtration membranes with large pore sizes were used in various sample digestions. Moreover, even those who used filters in the nano range were further limited by the detection techniques. FTIR and Raman spectroscopy were the most commonly used techniques, although these have a lower size detection (1µm) threshold, rendering them inadequate for reliable analysis of nanoparticles. Other thermal analytical techniques, such as Pyrolysis-GC/MS do not provide particle information, rely on complex data, are destructive and are intended for use coupled with other techniques; this however would further increase the complexity and cost (Leslie et al., 2022a; Mariano et al., 2021).

A total of 28 polymer types were detected based on their chemical composition and reference spectral libraries (Figure 6). One study, using Nile red solution for a staining protocol and quantification via fluorescence microscope, was unable to assign some polymers and labelled these as 'unidentifiable' (Horvatits et al., 2022). In the circulatory system, thrombi studies reported the prevalence of Polyamide (PA), a textile/fiber related polymer commonly used in industrial fibers and medical textiles. Wang et al., (2024) recorded a predominant presence of PA (PA66) in the size range of 20-50 µm from patients who had undergone thrombectomy due to Ischemic Stroke (IS), Myocardial Infarction (MI), or Deep Vein Thrombosis (DVT). A percentage of 81.3% PA was registered in thrombi samples obtained from patients diagnosed with IS, 40% for MI, and 100% for DV thrombi. The remaining percentages were Polyethylene (PE) (T. Wang et al., 2024). Similarly, Low Density Polyethylene (LDPE) was the only polymer detected in a further thrombi study (D. Wu et al., 2023). One study conducted on blood samples obtained in the UK reported a prevalence (32%) of PE (Leonard et al., 2024) again, whereas a Dutch study found levels of Polyethylene Terephthalate PET corresponding to 50%, followed by PE (23%) (Leslie et al., 2022a). In the arteries, PET was once again the most widely abundant particle detected (73%) in a study of the arteries, followed by 15.54% PA-66 (Liu et al., 2024). However, venous tissues were richer in alkyd resin (45%) (Rotchell et al., 2023).

Conversely, samples obtained from the digestive system reported Polyvinylchloride (PVC) as the dominant polymer in the small (59.8%), and large intestines (88.4%), in the tonsils (46.2%), and in the lungs (50.8%), followed by smaller amounts of Polypropylene (PP) (Zhu et al., 2024). How-

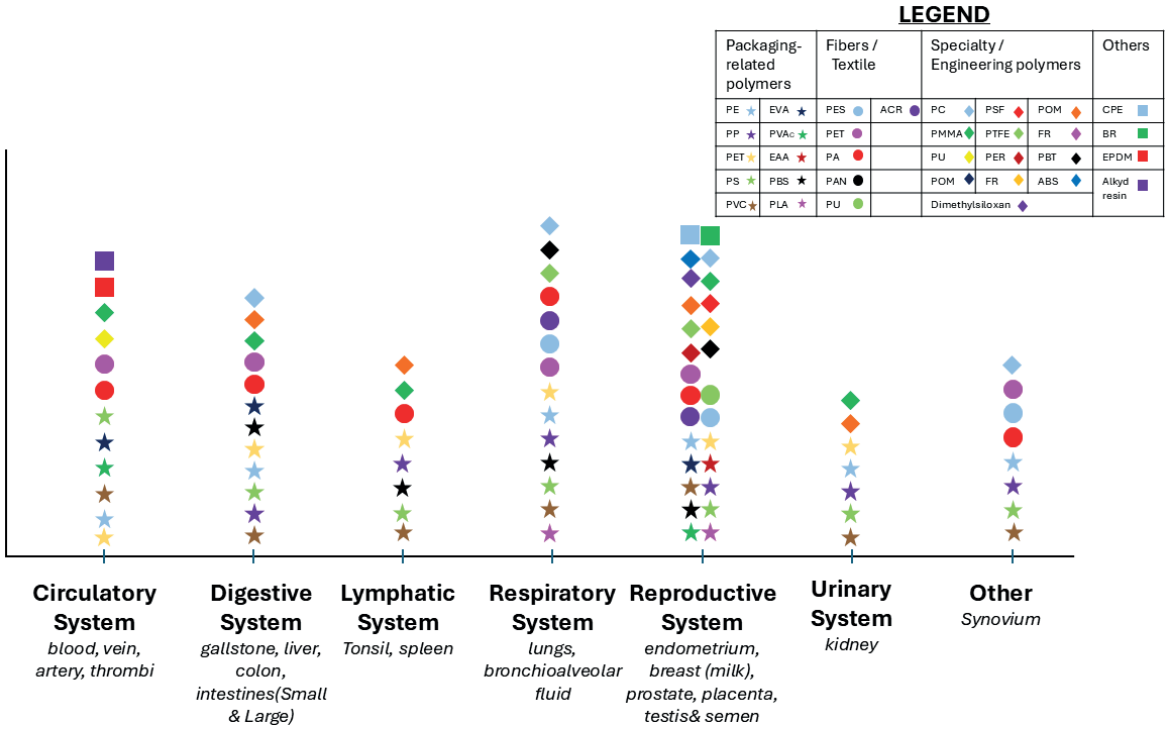

FIGURE 6: Microplastic polymer types detected in various human body systems.

ever, high levels of PP were found in parenchymal tissue from the distal and proximal regions of the left lung (35%) as reported by Amato et al., (2021) in Brazil; this finding was similar to the 23% obtained by Jenner et al (2022) in the UK. Moreover, a study conducted by Chen et al., in 2023 in samples from bronchoalveolar fluid likewise recorded a dominance of PP with a percentage of 41.9%, although an additional study of bronchoalveolar fluids delineated rayon/viscose as the most widely encountered polymer with a prevalence of 40.5%.

Therefore, these findings seem to imply that plastic packaging, including PE, PET, PP, and PVC, is the most widely prevalent polymer in the circulatory and digestive systems, consistent with their environmental availability and dominance in food contact materials. Meanwhile, fibers including PA and rayon are recurrent in the bloodstream and respiratory tissues, likely reflecting inhalation and possible dermal contact with synthetic fibers. The prevalent entry pathway of MNPs into the human body would be water/food contamination derived from the consumption of contaminated fruits and vegetables (Oliveri Conti et al., 2020), seafood, salt, honey, beer, tap water, and contamination from the films and wraps enclosing these beverages combined to air pollution (indoor and outdoor) (Cox et al., 2019). These findings therefore support the notion of ingestion and inhalation acting as the dominant pathways for MNPs transmission (Zhu et al., 2024; Y. Li et al., 2024)

In the male genitalia, PS alone represented 67% of the total amount of polymers detected in the testis, with the same study recording PVC and PE as most abundant in semen (25% each) (Zhao et al., 2023). Another study reported PS as the polymer most widely present in semen with levels of 31% (N. Li et al., 2024). In women, placental tissues were found to be abundant in PE- with levels of 54% detected by Garcia et al., (2024) and 43% by Amereh et al., (2022), Zhu et al. in 2023 found PVC to be more prevalent (43.2%) (Zhu et al., 2023). A further study reported the prevalence of PA and PU with a percentage above 74% in samples from the placenta and breast milk (Liu et al., 2023). Weingrill et al., (2023) conducted 3 follow-up studies of MNPs in the placenta across three different years, recording PP as the dominating polymer in 2006 and 2013, however, in 2021, PES was the most widely present polymer with a percentage of 13%, thus attesting to an increased concentration and enrichment in polymer diversity produced by exposure over time. The reproductive system appears to be equally susceptible to the translocation of packaging and textile-related polymers from ingestion and inhalation. This is highly influenced by lifestyle, environmental sources, and particle characteristics, which enable the polymers to cross human biological barriers and accumulate in deep sites of maternal and fetal tissues.

MNPs (PA, PU, PE, PVC, PP, and PES) may potentially possess the ability to cross significant biological barriers, such as the blood-placenta barrier, to reach the offspring; further research should therefore be carried out to determine possible health implications for both the mother and fetus, and to bridge a significant gap in our understanding by investigating the susceptibility of other biological membranes such as the blood-brain barrier to contamination (Kopatz et al., 2023; Rajendran & Chandrasekaran 2023).

Furthermore, engineering polymers are less frequent, yet also detected in these tissues with multiple barriers such as PC, POM, and PMMA, in the lymphatic, urinary and reproductive tissues. Although less frequent, their occurrence should set an alert as they are typically used in medical devices, coatings and more robust industrial applications. Their presence may suggest procedural routes, yet their health risks are still unknown.

The heterogeneity of polymers found across the studies examined may be due, at least in part, to regional variations, limited sample sizes, and methodological disparities. This has indeed somewhat hampered comparison with the other metrics studied, including the concentration of MNPs. Accordingly, analytical techniques should be standardized to ensure the yielding of uniform data, to capture the extent, distribution, and potential health impacts of microplastic contamination across diverse populations and environments.

3.1.3 Color and shapes

A wide range of shapes of MNPs have been detected in the human body, including spheres, sheets, pellets, granules, block-shaped, film, fibers, fragments, and irregular shapes. In particular, the detection of fibers and fragments, the presence of which is possibly due to their good mechanical properties (chemical stability and resistance to wear) underlying their widespread global usage (Yang et al., 2023) has been widely reported (Figure 7). Fibers however may prove difficult to remove from the human body, being detected in bronchial fluids as well as to a greater extent deep within the lungs (Baeza-Martínez et al., 2022; Jenner et al., 2022). Samples obtained in Spain from fluid sampled from the lower airways of patients undergoing bronchoscopy revealed a 93% abundance of particles shaped as fibers with sizes between 140 µm-9.96 mm (Baeza-Martínez et al., 2022). In lung tissues, a slightly higher percentage of fibers (49%) was recorded versus fragments (43%) between (12µm and 2mm) (Jenner et al., 2022). Nonetheless, bronchoalveolar lavage fluids also recorded a higher percentage of fragments, with 48.7% > 24.1% of fibers within a smaller size range (1-20µm) detected in Chinese children diagnosed with pulmonary diseases (Chen et al., 2023), and from lung samples obtained in Brazil from 20 coroner autopsies of people who died from pulmonary issues (87.5% fragments and 12.5% fibers within 1 and 5µm) (Amato-Lourenço et al., 2021).

In blood samples, 88% of all particles detected were white fragments (Leonard et al., 2024), similar to observations made in placental tissues in a study conducted in China, which harbored fragments in ample quantities. In this study, the size range of 20-200 µm was most abundant (70%), whilst a total of 50% of microplastics larger than 200 µm were represented by fibers (Ragusa et al., 2022; Zhu et al., 2023). As also reported in an Iranian study, a tendency was observed whereby smaller particles typically presented as fragments, with particles measuring 2.9 -35 µm were dominated by fragments in both normal and IUGR placentas (Amereh et al., 2022). This finding may support

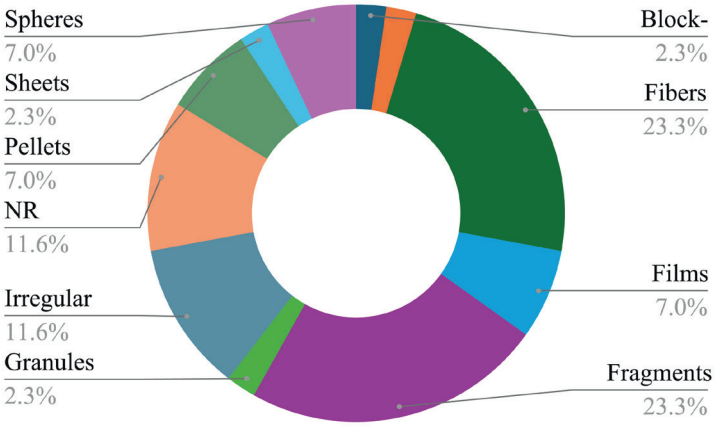

FIGURE 7: Overview of MNP polymer shapes identified within the human body across multiple studies. The figure presents raw frequencies, reporting observed occurrences rather than globally representative proportions. Interpretation should take into account differences in analytical methods, study design and reporting details among studies (NR stands for Not Recorded).

the notion according to which it is the actual structure of the fibers to enable them to resist biological clearance mechanisms, thus rendering the fiber more persistent and suggesting a lower propensity to breaking down and moving into the circulation.

Likewise, fibers/filaments found in the digestive system accounted for over 96% of particles in colon tissues, all measuring in the range of 0.8-1.6mm (Ibrahim et al., 2020). The tonsils, small and large intestines however, recorded a high prevalence of fragments in the size range of 20 -500 µm (Zhu et al., 2024). These findings therefore confirm that smaller particles tended to be fragments, meanwhile fibers were usually longer. Such size and shape distribution suggests distinct exposure pathways and transport mechanisms. Large fibers are likely ingested or inhaled, and after undergoing breakdown, suffer limited shape altering as compared to fragments, which are usually the product of continuous fragmentation.

3.1.4 Effects of MNPs in human tissues

The identification of different polymers in human tissues has raised serious concerns over potential health effects. Numerous studies are currently being carried out to ascertain the fate of these polymers in the body. Factors such as polymer types, particle size, and surface properties promote MNPs movement and interactions throughout the human body and influence the formation of the protein corona capable of providing them with a new biological identity and mediating surrounding interactions (Du et al., 2023). The results of toxicity tests performed by various authors using in-vitro culture mediums have been outlined in Table S4 of the supplementary materials. The different cell lines studied include the ovarian granulosa cell line, macrophages/blood cells, lung, colon, and intestinal cell lines, liver, placenta, kidney, brain, lymphocytes, cardiomyocytes, testicular and neural stem lines. PS represents the most widely investigated polymer across the entire body, although a wide array of polymers such as PET, PP, PVC, PA, and PE, in order of recurrence, is detected in various body tissues. PP is the most widely used, particularly in food packaging, whilst PVC, featuring a high hazard score and potential to cause health defects, is predominantly used in building and construction and has been detected throughout numerous body tissues (Zhu et al., 2023). Nonetheless, despite the finding of the significant presence of the latter two polymers throughout the human body, their potential for harm seems to be largely overlooked. Indeed, two of the selected studies evaluated the risk associated with PP and PVC in the human body. The first described a molecular dynamic simulation using lung surfactants (LS) (Li et al., 2022), whilst the second investigated the impact of these polymers on human monocytic THP-1 cells (Zingaro et al., 2023). Both polymers proved capable of causing harm, although more extensive studies are needed to allow more definitive conclusions to be drawn with regard to the impact of these polymers on human health.

An in-vitro model in which human M1 macrophages (macrophages responsible for mediating pro-inflammatory response through production of cytokines such as TNF-α, IL-1β, and IL-6) were exposed to 20µg/mL of PP and PVC caused oxidative stress as they increased the lipid content and changes in the cellular components. However, the authors concluded that cell viability remained high (Zingaro et al., 2023), in the same way as the results of a study investigating exposure of human lymphocytes to doses of PE (10-45 µm) exceeding 25 -500 µg/m - these cells continued to display no significant signs of cytotoxicity although genomic instability was observed (Çobanoğlu et al., 2021). Some degree of discrepancy was observed in two other models when similar bloodlines were exposed to smaller sizes of PS nanoparticles (50-500nm), resulting in cytotoxicity and a loss of mitochondrial membrane potential. At 200 µg/mL hemotoxicity was observed, with elevated ROS and lactate dehydrogenase production (LDH), consequently leading to cell death, indicative of a size and dose response to PS. In another study, human bronchial epithelial cells (BEAS-2B) were exposed to PS particles with a similar concentration to that used above, with an average size of 100nm, resulting in the finding that positively charged particles induced toxicity and increased ROS (Jeon et al., 2023),

thus highlighting the role of surface charge in addition to size and dose effect of MNPs toxicity in human tissues.

Although considerable advancements have been made in the search for plastics in the blood, further studies are needed to dispel any existing discrepancies with a view to ascertaining the multidimensionality of MNPs and investigate their affinities, interaction, and internalization under a series of direct physiological conditions (such as blood flow, tissue interaction, and cellular environments). For example, the sizes of polymers currently used for in vitro culture mediums and simulations cover only a small portion of the actual sizes detected in the human body. The particles studied are mostly in the ranges of 15 nm-10 µm, meanwhile, those actually detected are dominantly in the micro range of 1-500 µm. Regarding the concentrations to which these tissues are exposed, µg/mL is the most widely used unit of measure, with samples being obtained in liquid suspensions and their mass recorded per volume. Difficulties however may arise during the comparison of loads naturally detected from tissues versus loads tissues are exposed to during experimentation. Nonetheless, among the studies that detected MNPs in the human body, the two studies carried out in blood samples recorded concentrations ranging from 0.1-7.1 µg/mL (Leslie et al., 2022b; Leonard et al., 2024), considerably lower than the doses to which cells are exposed in culture mediums. For example, the concentration of PS to which lung, colon, and liver cells were exposed was studied by Peng et al., (2023), detecting an abundance ranging from 114 to 568000 particles/mL (Peng et al., 2023), i.e. three orders greater than that found in the blood (1412-10729 particles/l) (Leonard et al., 2024). This disparity underscores the challenge of translating toxicological findings into environmentally realistic scenarios. Nonetheless in vitro models are inherently limited by short exposure durations, whereas real-world exposures often span years, allowing for progressive accumulation and potential long-term effects, even at low concentrations. Therefore, while high-dose experiments remain valuable for elucidating dose–response mechanisms, their outcomes should be interpreted with caution when extrapolating to actual exposure conditions..

As highlighted in the present section, in vitro studies typically employ particles of smaller dimensions—generally nanoplastics—compared to those investigated in human and animal tissues. In general, the reduction in particle size from microplastics to nanoplastics significantly increases their toxicological potential, as smaller particles exhibit enhanced cellular uptake, deeper tissue penetration, and systemic distribution. Nanoplastics are associated with oxidative stress, inflammation, genotoxicity, and endocrine disruption, and can cross biological barriers such as the blood-brain barrier and placenta (Bhardwaj et al., 2025; Leslie et al., 2022; Yong et al., 2020). Dynamic or mechanical models may be able to provide valuable insights into these complex interactions, thus complementing data gathered from biological human models by predicting the transport and toxicity of contaminants across a wide range of scenarios without invasive procedures in animals and humans.

3.1.5 Mechanical modelling of MPs in the human body

In vitro, in vivo, and ex vivo models have been extensively employed to investigate the kinetics of MNPs across various species, including humans. These models have provided valuable insights and contributed towards advancing knowledge of their potential health impacts on humans as portrayed in the toxicological effects in Table S4 of the supplementary materials . Research has identified the three primary mechanisms through which MNPs exercise toxicity, which include: (1) mechanical stress on cells due to their physical properties, (2) chemical toxicity resulting from the leaching of additives, and (3) serving as vehicles for other contaminants, facilitating entry into the human body. MNPs encompass such a huge diversity of properties and exploring them all may prove too cumbersome and potentially pose ethical issues if explored using animal models alone. Mechanical models are peculiar in that they incorporate parameters such as particle characteristics, biological transport mechanisms, and controlled tissue-specific kinetics. These could provide a more comprehensive predictive framework to assess the potential risks posed by MNPs in the human body.

Early in 2013, a computational study involving coarse grain simulations and molecular dynamics was carried out in France to assess the impact of PS nanoparticles on phospholipid membranes (Rossi et al., 2014). Based on this study, the ability of the PS nanoparticles to penetrate and impact the structural and mechanical properties was predicted. However, the authors pointed out a lack of direct experimental verification and high computational cost of this study over the relevant length and time scales. Bochichio et al., (2021) later overcame these issues through use of a combination of experimental techniques (calorimetry, x-ray, and neutron scattering) with atomistic molecular dynamics simulations to study the interactions between short chains of PS and dipalmitoyl phosphatidylcholine (DPPC) lipid bilayers (Bochicchio et al., 2022). Once embedded in the DPPC lipid bilayer core, nano-sized PS decreased their pre and main transition temperatures, stabilizing the lipid fluid phase while reducing system cooperativity in a dose-dependent manner. However, the same data might also have suggested that above a certain threshold, the system would undergo partial phase separation. Using a coarser model compared to earlier experimentation in 2013, molecular dynamics simulation provided an interpretation at an atomic level, confirming PS as producing a mechanical softening and overall disordering effect. PE was also studied using molecular dynamics simulation to understand the effects of nanoscale PE on the DPPC bilayer. Key properties of the DPPC membrane were affected, causing lower density, fluidity changes, membrane thickening and clusters of PE at high concentrations, thus tending to cause pore formation in the DPPC bilayer (W. Wang et al., 2022). As in previous studies, the overall results obtained confirmed the alterations of properties of DPPC, the perturbation of membrane structure and dynamics, and eventual modification of the mechanical properties of these membranes (Bochicchio et al., 2022; Hollóczki & Gehrke 2020; Wang et al., 2022).

Computational fluid dynamics (CFD) simulations include different variants intended to describe the effect of MNPs on airflow and lead to lung infection/disease. This includes the discrete phase model, the Eulerian-Lagrangian approach, single or multiphase models, and laminar or turbulent models. When coupled with molecular dynamics simulation, they have been jointly proposed as a means of predicting what happens following the deposition of micro and nano plastics in the respiratory tract and interaction mechanisms at various levels of complexity (Saha & Saha 2024). Anatomical features have been repeatedly suggested as influencing the accumulation and clearance of MNPs in the respiratory tract; however, definitive conclusions remain limited due to small sample sizes and methodological variability across studies (Jenner et al., 2022; Zhu et al., 2024). Findings from CFD studies on polydispersed particles in the lungs (Islam et al., 2019) confirmed the veracity of this factor alongside other parameters such as gravity, flow rate or breathing pattern, and the chemical and physical properties of the plastic particle (Islam et al., 2023; Saha & Saha, 2024). In addition to the detailed insights into flow dynamics, models such as Multiple-Path Particle Dosimetry (MPPD) and CFD simulations could alleviate the uncertainties in sex- based interpretation by standardizing anatomical inputs and isolating the effects of morphology from other factors, thereby offering a more controlled framework to understand particle deposition and clearance mechanisms. Also, it will facilitate the design and optimization of medical device treatments for lung diseases and could significantly reduce the need for animal testing and human trials, thus saving time, money, and ethical problems. Furthermore, these simulations foster collaboration between several diverse fields to address the common issue of micro and nano plastics (Saha & Saha 2024).

3.2 Micro and Nano plastics in animal tissues

As seen in human samples, microplastics have been identified throughout numerous body systems in mammals (Table S3 of the supplementary materials). These include the digestive (stomach, forestomach compartments, liver and intestine), respiratory (lungs), reproductive (epididymis, testicular, prostate and sperm), urinary (kidneys), musculoskeletal, circulatory and lymphatic systems. Animal species investigated include bats (*Chiroptera spp.*) in Brazil (Alencastre-Santos et al., 2024; Correia et al., 2024), cows (*Bos taurus*) and sheep (*Ovis aries*) in Iran (Bahrani et al., 2024), the European brown hare (*Lepus europaeus*) in Austria (Hornek-Gausterer et al., 2021), bulls in Germany (Grechi et al., 2024), pigs (*Sus scrofa*) in China (Li et al., 2023), dogs (Canis familiaris) and cats (*Felis catus*) in Portugal and the US (Hu et al., 2024; Prata et al., 2022) and various rodents in China and Italy (Nessi et al., 2022; Yang et al., 2024). The age and gender information of these mammals were cited solely for descriptive purposes, but no statistical analyses were performed.

Only a few studies have reported qualitative and quantitative descriptions of MPs in animals versus human samples, with a range of reporting units being used across studies, although 4 out of 7 papers reported in particles/g, as seen in Figure 8. Among terrestrial mammals, plastics were detected at a concentration of 180 particles/g in the 20.34 µm-916.36 µm size range in the lungs of a domestic pig, and 97 particles/g in a shorter range of 20.34 µm -501.49 µm in pig fetuses (Li et al., 2023). This concentration of MPs in domestic pigs is ten times greater than the

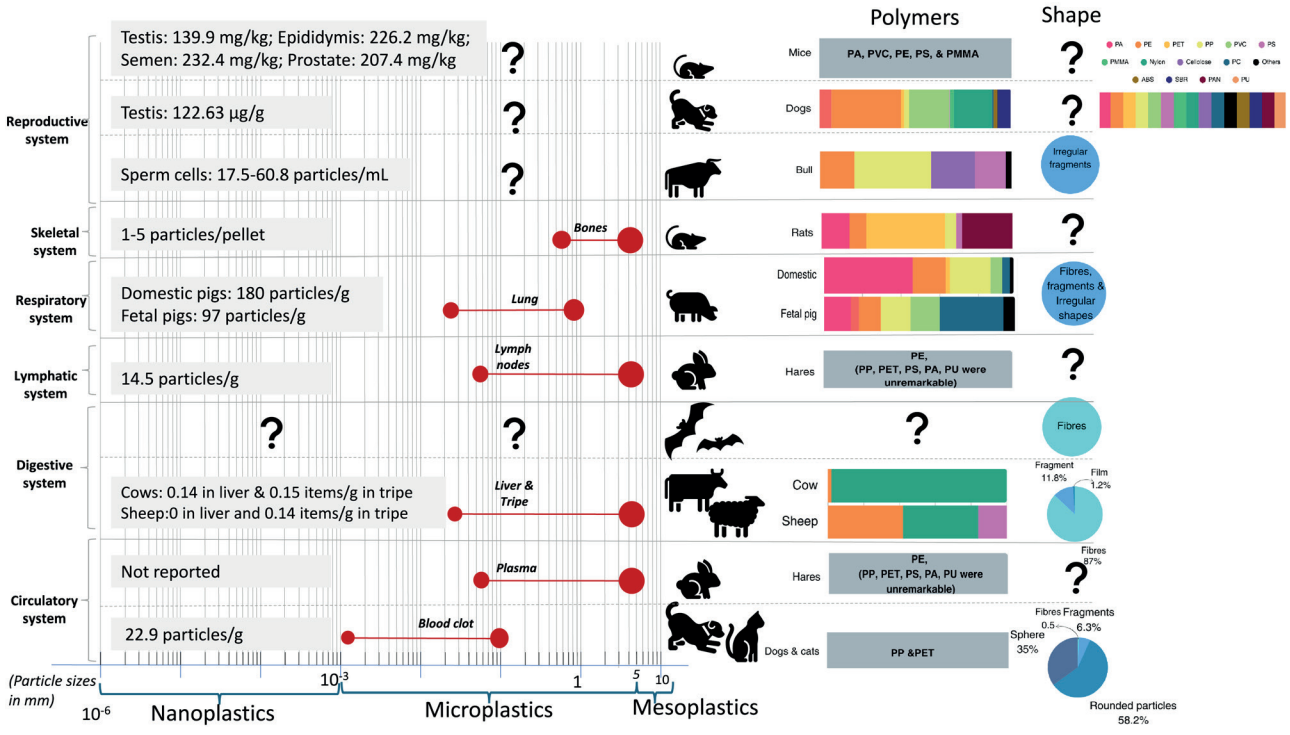

FIGURE 8: Overview of MNPs in animals' tissues. Question marks denote missing and unclearly stated information.

maximum amount obtained from human lungs (14.19 particles/g as captured by Zhu et al., (2024)), considering that both used the laser direct infrared spectroscope for identification. Although the detectable size range of MPs identified in the pig analysis was broader compared to humans, the considerably higher concentrations suggest that particle size alone cannot account for the difference. However, this study encountered the limitation of sample size given that only one pig was sampled and, therefore, comparison was limited to the fetal pigs also analyzed in this study. However, to strengthen the argument and substantiate the conclusion, a larger sample size would be necessary.

Tissues from the lungs, liver, kidney, ileum and blood were sampled from dogs and cats in a study conducted in Portugal, which reported a median of zero particles (0 particles/g) for the majority of tissues, although recording a median of 22.9 particles/g in a size range of 1-100 µm (Prata et al., 2022) for blood clots. In this sample type, only two polymers (PP and PET) were detected. It is worthy of note that PET was also one of the most widely prevalent MPs in the human circulatory system, possibly since it is typically used in the production of clothing and home textiles in the form of polyester fibers. It is at times combined with cellulose-based fibers such as cotton, linen and hemp, to improve softness, versatility, durability and other properties (Periyasamy & Tehrani-Bagha 2022). MPs were mostly rounded particles and spheres in blood samples from dogs and cats as opposed to fragments (88%) in human blood (Leonard et al., 2024), likely resulting from exposure to microbeads from household items, contaminated pet food as well as pet shampoos and other grooming products. Furthermore, dogs and cats have shorter digestive tracts compared to humans, thus potentially facilitating the uptake of round particles, which present with a more uniform geometry (He et al., 2024). A meaningful comparison of loads could not be achieved due to methodological differences due to the use of different reporting units. Moreover, the use of blood clots may have implied increased microplastic concentrations due to sedimentation and particle entrapment during the coagulation process.

Regarding the lymphatic system, a concentration of 14.5 PE particles/g was quantified in the mesenteric lymph nodes of European brown hares (Hornek-Gausterer et al., 2021). However, when compared to investigations in the human immune system (spleen: 6.03particles/g and tonsil: 0.9 particles/g), the concentration of MPs detected in European brown hares was significantly higher (Horvatits et al., 2022; Zhu et al., 2024). These findings, however, may have been influenced by detection limits as only particles over the size of 50µm were recorded in hares, thus providing a broad size range of MPs yet excluding smaller particles. Meanwhile, in human studies, particle size ranged between 4 and 30µm for spleen samples and between 20.34 and 471.87 µm for tonsil samples, thus allowing for detection of microplastics despite covering an overall smaller size spectrum. Aside from the methodological differences in detection sensitivity, variation in the immune system function across species and greater exposure to the outdoor environment (soil, air and vegetation) might have contributed to the higher concentrations observed in animals compared to humans.

Cow and sheep tissues obtained from a butcher shop in Iran had the smallest concentration of MPs, recording a predominant 86.9% of fibers (liver: 0.14 particles/g in cows and 0.0 in sheep; tripe: 0.15 particles/g in cows and 0.14 particles/g in sheep). Analyses conducted on liver samples recorded the smallest concentration (3.2 particles/g) and smallest size range of MPs among tissues from the human digestive system (Horvatits et al., 2022), but still far greater than MPs detected in animal tissues utilizing similar methodological options (i.e. micro-Raman spectroscopy). Ruminants have a multi-chambered stomach, with fermentation and microbial action that might perhaps break down or trap microplastics more effectively than humans (Quartinello et al., 2021). Again, their longer digestion times in the rumen may allow larger or denser particles to settle, be excreted or become immobilized, thus explaining their low concentrations in the digestive system; more studies would however be needed to corroborate these theories (Dehority 2002; Dufreneix et al., 2019).

Notably, the male reproductive organ of mice revealed elevated concentration of MPs, particularly in semen (232 mg/kg), the epididymis (226 mg/kg), the prostate (207.4mg/kg) and the testis (139.9 mg/kg) (W. Yang et al., 2024). In comparison, slightly lower concentrations were quantified in dog testis (122.6 mg/kg) although with a higher polymer diversity (Hu et al., 2024), suggesting that dogs might be more exposed to a greater range of polymers whilst displaying a lower bioaccumulation potential compared to mice. However, definitive conclusions cannot be drawn due to a lack of information regarding particle sizes which influence bioavailability, combined with the varying exposure intensities and differences in geographical location. In the same way as human tissues, these results reveal the ability of MNPs to cross the blood-testis barrier and confirm their presence in regions critical for spermatogenesis and hormonal functions, therefore posing risks for male fertility and compromising embryo development (Grechi et al., 2024).

Current research focused on the identification and characterization of MPs in terrestrial animals has provided a valuable investigation baseline. However, MPs detection in animal tissues remains an understudied topic, limiting the understanding of systemic distribution and potential long-term impact on animal health. Moreover, meaningful comparison across studies is complicated by inconsistent methodologies, varying units of measurement and lack of standardized detection thresholds. These laboratory protocols must be harmonized to ensure reliability, comparability and reproducibility of findings across both species and research contexts.

Beyond analytical challenges, a deeper understanding of upstream drivers is increasingly urgent. The presence of MNPs in terrestrial ecosystems is closely linked to the broader context of waste management practices. Plastic contamination in soils and terrestrial food webs can be traced to several sources, including improper disposal (e.g., littering), the reuse of waste-derived amendments such as compost, sewage sludge, and digestate on agricultural land, and emissions from recycling and solid waste treatment processes, particularly through atmos-

pheric depositions and runoffs (Adhikari et al., 2024; Corradini et al., 2019; Meixner et al., 2020; Porterfield et al., 2023. Interestingly, the recent discovery of a pathogenic microorganism capable of degrading PET (Srivastava et al., 2024), identified in certain solid waste treatment facilities, raises important questions about whether such microbial adaptations may be driven by prolonged exposure to plastics, materials that offer relatively hospitable conditions. This connection could be crucial for advancing our understanding of both the persistence of MNPs and potential degradation pathways within terrestrial ecosystems. Moreover, it underscores the need for targeted interventions across the entire plastic lifecycle, from production to disposal.

3.3 Critical methodological limitations in the detection of MNPs in biological tissues

As has been highlighted multiple times in earlier parts of the text, micro- and nanoplastic investigation presents several methodological limitations, including:

- The lack of a standardized analytical protocol: there is no universally accepted method for sample processing, extraction, and identification of MNPs in biological tissues. Studies use different digestion techniques, filtration steps, and detection technologies (e.g., FTIR, Raman, Py-GC/MS), each with specific size detection limits and biases. This leads to inconsistent dimensional ranges, units of measurement, and reporting formats across studies (Ośko et al., 2025);
- Limited comparability due to diverse technologies: in fact, different analytical methods vary in sensitivity, specificity, and resolution. For example, FTIR typically detects particles >10 µm, while Raman can reach ~1 µm, and thermal methods like Py-GC/MS detect polymer types but not particle size. This technological heterogeneity makes cross-study comparisons difficult (Shao et al., 2025);
- Matrix complexity and contamination risks: biological tissues are complex matrices that require careful digestion and purification. Sample loss, contamination from labware or airborne particles, and adhesion to surfaces can distort results (Stock et al., 2020). Contamination mitigation strategies are critical in MNPs analysis, particularly in biological matrices, where environmental and procedural contamination can severely compromise data integrity. Therefore, rigorous preventive measures must be implemented at every stage of MNPs sampling and analysis. This includes avoiding the inadvertent introduction of anthropogenic particles — those not originally present in the environmental sample — via sources such as laboratory surfaces, airborne deposition, analysts' garments, or equipment in use. Such contamination can significantly distort particle counts and compromise data integrity (Poli et al., 2024). Protocols for contamination prevention — such as the use of clean-air cabinets, cotton lab coats, procedural blanks, and pre-rinsed glassware — are essential to avoid overestimation of MP abundance (Huang et al., 2024; Stock et al., 2020). Recent findings demonstrate that procedural contamination can substantially inflate microplastic counts in biological samples. Aminah & Ikejima, (2023), showed that implementing basic mitigation strategies reduced contamination levels by 70-100%, underscoring the critical need for rigorous protocols in microplastic research. While studies on MNPs often lack the inclusion of rigorous blank controls and contamination mitigation strategies, this was not the case in the selected studies for the present review. All reviewed studies implemented plastic contamination protocols to ensure data reliability, including the use of procedural and/or environmental blank controls. Only a few exceptions were noted where the inclusion of blanks was not explicitly stated: Correia et al., 2024; Ragusa et al., 2022; Zhang et al., 2024;
- Inadequate particle morphological characterization: many studies fail to report key particle attributes such as shape, surface chemistry, polymer type, and aggregation state (Alencastre-Santos et al., 2024; Correia et al., 2024; Hornek-Gausterer et al., 2021; Horvatits et al., 2022; Hu et al., 2024; N. Li et al., 2024; Z. Li et al., 2024; Liu et al., 2023, 2024; Nessi et al., 2022; Ragusa et al., 2022; Wang et al., 2024; Yang et al., 2024; Zhang et al., 2024). These factors critically influence biological interactions and toxicity but are often overlooked due to analytical constraints (Ośko et al., 2025);
- Lack of harmonized units and exposure metrics: studies report MNP concentrations using different units, making it difficult to compare exposure levels or establish dose–response relationships (Huang et al., 2024). This aspect has already been addressed in the manuscript, specifically in Section 3.1.1 and illustrated in Figure 4, where we detail the units adopted across studies involving human samples — namely, number of particles per gram of tissue, micrograms of MNPs per gram of tissue, and number of particles per liter for liquid matrices. Additionally, Section 3.2 Micro- and nanoplastics in animal tissues outlines the units used in animal studies, which predominantly include the number of particles per gram of tissues and, in some cases, milligrams per kilogram, particles per microliter, and particles per pellet. This heterogeneity complicates cross-study comparisons.

Taken together, these methodological limitations significantly hinder the ability to perform structured and meaningful comparisons across studies. The lack of harmonized protocols for sampling, sample processing, analytical techniques, and data reporting not only compromises reproducibility but also obstructs the development of robust dose–response relationships and risk assessments. As the field of MNP research continues to expand, there is an urgent need for the scientific community to establish and adopt uniform standards that ensure consistency, transparency, and comparability across investigations (Poli et al., 2024). Such harmonization is essential to advance our understanding of MNP distribution, toxicity, and potential health impacts in both human and animal systems.

4. CONCLUSIONS

Both humans and other terrestrial mammals have been shown to host microplastics across a wide range of body tissues and cells. While human studies have revealed a broader diversity of polymers, terrestrial animals have been reported to host greater quantities. Moreover, unlike aquatic media in which MNPs could be attributed only to ingestion, the inhalation of airborne particles from both indoor and outdoor environments adds to ingestion as an important entry pathway of MNPs into the systems of terrestrial mammals.

Despite growing evidence, gender and age specific analyses remain scarce. These biological variances may significantly influence MNPs exposure, accumulation and physiological response across species and should be integrated into future research.

Another major challenge lies in the lack of standardized protocols, which may have contributed to the broad variability observed in reported data for both human and other terrestrial mammals. Sample pretreatment methods may influence the recovery of particles while the use of sieve filters imposes arbitrary size thresholds. Furthermore, the variety of analytical instruments, each with differing sensitivity, resolution, and suitability for specific size ranges or polymer types, adds to data inconsistency and hampers accurate exposure assessments. This variability often makes the detection of nanosized particles unattainable and renders cross-study comparisons unreliable. To overcome these limitations, a universally accepted and harmonized analytical framework is urgently needed. However, it is worth noting that quantitative integration across exposure pathways of MNPs remains premature, given the said limitations. A holistic perspective which captures a full quantitative integration would require the understanding of multiple stressors, their co-existence in the exposome, which is summed up in all internal and external exposures, intake rates, and as well as the biological response, such as absorption efficiency in respective tissues. Therefore, addressing these limitations in new studies could pave the way towards a more integrated and realistic assessment of MNP exposure in human and animal tissues.

Health-related risks associated with exposure to MNPs have been documented across a wide range of tissues and cell lines, revealing effects such as induced apoptosis (cell death) due to oxidative stress, disruption of cellular functions, and inhibition of specific bacteria and enzymes. While current findings from in vitro, in vivo, and ex vivo studies provide a solid foundation, further research is essential to fully understand the complexities of these contaminants.

Computational Fluid Dynamics (CFD) simulations represent a promising tool to advance this field, offering the ability to model the fate and transport of particles with different physical and chemical characteristics (e.g. size, polymer type) under realistic physiological conditions. These simulations can predict biodistribution, accumulation, and potential toxicity hotspots across species. When combined with experimental data, CFD can contribute to a more comprehensive understanding of MNP behavior within biological systems, thereby supporting the development of more effective public health strategies.

In parallel, developing a framework for future studies could provide a practical foundation for advancement in this field. It is recommended that future studies encompass parameters responsible for route-specific estimated intakes of MNPs, as well as clearance and translocation coefficients. In addition, reported abundances should include conversion factors linking particle count to mass-based units, derived from particle-specific properties. This approach would enable more meaningful comparisons across exposure routes, support the development of robust mass-based models, and contribute to the harmonization of exposure assessments concerning the presence of these contaminants in terrestrial mammals and ecosystems more broadly.

Furthermore, considering the close ecological and biological connections between humans, animals, and the environment, an approach encapsulated in the “One Health” framework, there is a pressing need for interdisciplinary and integrative investigations. These efforts will be critical in mitigating the widespread health and environmental impacts of micro and nanoplastics.

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