POLYSTYRENE MICROPLASTICS: ENVIRONMENTAL PRESENCE, PATHWAYS, AND BIOLOGICAL IMPACT

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Abstract

The escalating accumulation of microplastics in the environment has emerged as a critical global issue, with significant implications for ecosystems and human health. Among the most prevalent and hazardous types are polystyrene microplastics (PS-MPs), widely derived from food packaging, insulation materials, and disposable consumer products. Due to their durability, low density, and resistance to degradation, PS-MPs are persistent pollutants that fragment into micro- and nanoplastics, infiltrating water, air, soil, and the food chain. Recent studies have confirmed their presence not only in diverse environmental matrices but also in human tissues, including the blood, lungs, liver, brain, and placenta. These particles have been shown to induce cellular stress, disrupt gene expression, alter microbiota, and trigger inflammatory and oxidative responses. This review provides a comprehensive overview of PS-MPs, highlighting their environmental distribution, exposure pathways, organ-level accumulation, and toxicological mechanisms. It also explores the analytical methods used for detection, such as Raman spectroscopy, FTIR, and pyrolysis-GC/MS. By identifying current knowledge gaps and future research priorities, this work underscores the urgent need for standardized methodologies and interdisciplinary strategies to assess, monitor, and mitigate the impact of PS-MPs on public health and the environment.

Keywords: *polystyrene, microplastics, nanoplastics, human health, tissue accumulation, environmental exposure*

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Introduction

The exponential growth in plastic production and consumption over recent decades has resulted in an alarming surge in microplastic pollution, prompting critical concerns regarding environmental sustainability, food security, and human health. Microplastics, commonly defined as plastic particles smaller than 5 mm [1], have been detected across virtually all ecosystems, including marine, freshwater, terrestrial, and even atmospheric environments [2]. These particles originate from both primary sources (e.g., microbeads in cosmetics) and secondary fragmentation of larger plastic debris [3]. Among the numerous synthetic polymers contributing to this global issue, polystyrene (PS) is particularly prominent due to its widespread application, unique physicochemical properties, and emerging evidence of adverse biological interactions [4], [5].

Polystyrene is a colourless, brittle, and lightweight thermoplastic derived from styrene monomers through free radical polymerization [2]. It is widely employed in the manufacture of disposable food containers, foam insulation, packaging materials, and various consumer products due to its low cost, moldability, and transparency [2]. However, its environmental persistence, hydrophobicity, and resistance to biodegradation render it especially prone to long-term accumulation in natural systems [4] [6] [7]. As PS products degrade under physical, thermal, photolytic, and chemical stressors, they generate micro- and nanoplastic fragments that can travel significant distances, infiltrating food webs, and bioaccumulating in diverse organisms [3], [6], [8]. Polystyrene degradation in environmental conditions involves multiple interconnected processes. Primary degradation occurs through UV-initiated photooxidation, where the aromatic phenyl groups absorb UV radiation ($\lambda \approx 260$ nm), transferring energy to adjacent C-H bonds and causing radical formation. This process generates ketones, carboxylic acids, aldehydes, esters, and lactones while reducing particle size at rates of approximately -24 ± 3.0 nm h^{-1} under controlled UV exposure [9], [10]. Environmental lifetime studies demonstrate that sunlight exposure dramatically reduces PS persistence compared to dark conditions. Recent research indicates that under peak terrestrial sunlight conditions, submicron PS particles (1000 nm) may degrade to nanoscale dimensions (1 nm) in less than 500 hours. This represents a significant revision from earlier assumptions of millennial-scale persistence, with photodegradation rates being 10-100 times faster than previously estimated [9], [11]. Mechanical fragmentation complements chemical degradation through wave action, sediment abrasion, and thermal cycling. Weathered PS exhibits increased fragmentation susceptibility due to surface oxidation and embrittlement. Combined UV-mechanical stress results in exponential fragmentation patterns, with smaller particles exhibiting higher surface area-to-volume ratios and accelerated degradation kinetics [12], [13], [14].

Lifetime prediction models indicate PS persistence varies dramatically with environmental conditions:

- Marine surface waters: 10-100 years (high UV exposure)
- Deep ocean/sediments: 100-1000 years (limited UV penetration)
- Terrestrial soils: 50-500 years (variable UV/temperature conditions)
- Arctic/polar regions: 500+ years (reduced UV intensity, low temperatures)

These estimates incorporate recent advances in photodegradation kinetics but remain subject to considerable

uncertainty due to variability in environmental stressors, polymer formulations, and additive compositions [9], [11], [14]. The varying environmental persistence of polystyrene directly reflects its global distribution. Recent studies have reported the presence of polystyrene microplastics in a broad array of environmental matrices, including surface waters, sediments, soils, and atmospheric fallout [3], [6]. These particles are frequently found in drinking water, seafood, and agricultural produce, suggesting multiple exposure pathways for both wildlife and humans [6], [15], [16]. More alarmingly, PS microplastics have now been detected in human tissues such as blood, lungs, liver, placenta, and brain, indicating their ability to cross physiological barriers and accumulate in critical organs [5], [17], [18], [19], [20], [21].

At the cellular and organismal levels, PS micro- and nanoplastics have been shown to induce a range of toxicological effects. In vitro and in vivo studies reveal that these particles can provoke inflammatory responses, disrupt the gut microbiome, impair cellular metabolism, alter gene expression, and generate oxidative stress, potentially contributing to chronic diseases and reproductive toxicity [2], [5], [22], [23].

The likelihood of systemic translocation and cellular internalization depends not only on particle size, with smaller nanoplastics posing a higher risk, but also on the polymer type, surface properties, and adsorbed substances, which influence their interactions with biological barriers. Nanoplastics, in particular, can traverse the blood-brain and placental barriers, posing an acute threat due to their ability to reach sensitive organs [17], [18]. Recent studies have demonstrated that both polystyrene (PS) and polyvinyl chloride (PVC) nanoplastics can cross the blood-brain barrier, with PVC particles exhibiting a higher penetration rate. However, the presence of a biological corona significantly reduced the amount of nanoplastics entering the brain, highlighting the complex interplay between particle composition and biological interactions [24]. Despite recent advancements in analytical chemistry and toxicology, significant knowledge gaps remain regarding the fate, transport, and long-term effects of PS microplastics in living organisms. The heterogeneity of PS particles in terms of size, shape, surface chemistry, and environmental weathering further complicates risk assessment and regulation [4], [25]. Therefore, this review aims to provide a comprehensive synthesis of the current state of knowledge on polystyrene microplastics, focusing on their environmental sources, routes of human exposure, tissue distribution, toxicological profiles, and methods of detection. By consolidating recent research findings, we seek to elucidate the role of PS in the broader microplastic crisis and identify scientific and policy-oriented strategies to mitigate its impact on ecosystems and human health.

Microplastics in Tissues

Following environmental exposure, microplastics can enter the human and animal body through three principal pathways: ingestion, inhalation, and, to a lesser extent, dermal contact [6], [17], [26], [27], [28], [29]. The most common route is the ingestion of contaminated food and water, including seafood and agricultural products [27], [29], [30], [31]. Inhalation of airborne particles, especially in urban or indoor environments, represents a significant additional source [26], [32], [33]. While dermal absorption of microplastics is still under investigation, current evidence suggests that its contribution is minimal compared to the other routes [15], [26], [34]. Once internalized, microplastics can accumulate in various tissues and organs, including the lungs, intestines, liver, kidneys, placenta, and even the brain [5], [17], [18], [19], [20], [21]. Particularly concerning are nanoplastics, which, due to their small size and high surface activity, can cross biological membranes and enter systemic circulation, potentially reaching distant and sensitive tissues [35], [36], [37], [38], [39]. Animal studies have revealed widespread microplastic accumulation in aquatic organisms such as fish, mollusks, seabirds, and marine mammals [6], [40], [41]. While these particles are most often found in the gastrointestinal tract, increasing evidence confirms their presence in secondary tissues like liver and muscle, suggesting systemic distribution [42], [43], [44], [45]. Terrestrial animals, including livestock and domestic pets, have also been shown to ingest and accumulate microplastics, which may pose risks for food safety and human co-exposure [46], [47], [48], [49]. From an ecotoxicological perspective, microplastics have been shown to induce a variety of adverse effects in animal models, including immune dysregulation, oxidative stress, endocrine disruption, and reproductive toxicity [6], [50], [51], [52]. Moreover, microplastics can act as carriers for hazardous substances such as heavy metals, persistent organic pollutants, and pathogenic microorganisms, thereby enhancing their overall toxic potential [53], [54]. In humans, microplastics have been detected in multiple tissues using advanced spectroscopic and imaging techniques [55], [56], [57]. Particles composed of polystyrene, polyethylene, polyvinyl chloride, and polyethylene terephthalate have been found in the lungs, intestinal tract, liver, bloodstream, and placenta [58], [59]. Concentrations tend to be highest in organs directly exposed to the external environment, such as the lungs and intestines [17], [57], [60]. Evidence also indicates that smaller particles can cross the blood-brain and placental barriers, raising concerns about potential neurodevelopmental and systemic impacts [35], [61], [62], [63]. Examples of the presence and effects of microplastics in human tissues are presented in Table 1.

TABLE 1. Presence and effects of microplastics detected in selected human tissues and organs

Tissue/Organ	Main Microplastic Types	Average Abundance (particles/g)	Notable Effects	Bibliography
Lung	PVC, PE, PS	Up to 14.2	Inflammation, oxidative stress	[17], [64], [65], [66]
Intestine (small/large)	PVC, PE, PET	6–9.5	Dysbiosis, barrier disruption	[17], [23]
Liver	Not always quantified	Data emerging	Possible metabolic impacts	[17], [67], [68]
Placenta	PE, PS, multiple types	Variable	Altered gene expression, inflammation	[17], [19], [69], [70]
Vascular system	Mixed	Nanoplastics also detected	Correlated with vascular disease	[17], [71], [72]

At the cellular level, exposure to microplastics has been associated with inflammation, oxidative damage, apoptosis, mitochondrial dysfunction, and impaired cellular signalling. In vitro and animal studies suggest that smaller particles (<100 nm) pose greater risks due to enhanced cellular uptake and intracellular reactivity [73], [74], [75].

Despite growing evidence of tissue-level accumulation and biological effects, major knowledge gaps remain. These include insufficient data on long-term exposure outcomes, a lack of standardized analytical protocols for tissue analysis, and a limited understanding of how particle properties (e.g., size, shape, surface chemistry) influence toxicity. Addressing these gaps will be crucial for accurate risk assessment and effective regulation of microplastics in both environmental and biomedical contexts.

Polystyrene in Human Tissues

Polystyrene (PS) is one of the most encountered synthetic polymers in the environment, primarily used in food packaging, insulation foams, and disposable consumer products [4], [76], [77]. Through the fragmentation of larger plastic waste, polystyrene microplastics (PS-MPs) are defined as formed particles smaller than 5 mm [2]. Due to their persistence and mobility in various environmental media, PS-MPs are increasingly recognized as a potential threat to human health. With a density of approximately 1.05 g/cm³, PS particles can remain suspended in water, facilitating their distribution in aquatic ecosystems and eventual entry into the food chain [78], [79]. Their physical and chemical properties, such as chemical resistance and optical clarity, contribute to their environmental accumulation and bioavailability.

In recent years, PS-MPs have been identified in multiple human tissues, including blood, lungs, liver, kidneys, brain, and placenta [21], [55], [58]. Particularly concerning are reports indicating their presence in a significant proportion of blood samples and their ability to cross critical biological barriers, including the blood–brain barrier [55]. These findings highlight the urgent need to better understand the mechanisms of PS-MP accumulation in the human body and their potential health implications.

Exposure and Distribution in the Body

Human exposure to PS-MPs occurs primarily via ingestion, inhalation, and, to a lesser extent, dermal contact [19]. Studies have shown that PS particles can penetrate the digestive and respiratory systems and, in certain cases, cross biological membranes. Nanoplastics – particles in the nanometre range – are of particular concern due to their capacity to breach the intestinal and blood–brain barriers [79], [80].

Initial evidence of PS-MPs in human blood has demonstrated their systemic circulation, with polystyrene ranking among the most frequently detected polymer types [20], [21]. Analytical methods such as pyrolysis–gas chromatography–mass spectrometry have confirmed the presence of PS particles ranging in size from submicron to hundreds of microns [21], [56].

Organ-Specific Accumulation

The lungs serve as a primary target for PS-MPs introduced via inhalation. Animal studies have shown that particle size influences deposition patterns, with smaller particles more likely to penetrate deep into lung tissues. Long-term exposure may contribute to pulmonary fibrosis, driven by inflammatory and ferroptotic mechanisms [22].

The liver, due to its central role in detoxification, is highly susceptible to PS-MP accumulation. In vitro and in vivo models have demonstrated the translocation of particles from the gut to the liver, resulting in oxidative stress and hepatocellular damage. Chronic exposure may lead to fibrotic changes and disruptions in lipid metabolism [42], [81].

The kidneys are another sensitive target. Research has shown that PS-MPs can induce mitochondrial dysfunction, endoplasmic reticulum stress, and autophagy in renal tubular cells. These processes may contribute to cellular senescence and kidney fibrosis [5], [82].

The brain is also vulnerable to PS-MP accumulation. Studies have shown that PS particles can be detected in brain tissue within hours after oral exposure. A key mechanism is the formation of a biomolecular corona on particle surfaces, facilitating their passage across the blood–brain barrier. Accumulation in neural tissue has been associated with neurological and behavioural alterations [55], [61], [83], [84].

Finally, the placenta represents a particularly concerning site of PS-MP accumulation. Studies have identified PS particles in all examined placental samples. Exposure has been linked to cytotoxicity, oxidative stress, and metabolic disturbances, raising concerns about fetal development and transplacental transfer of microplastics [19], [70]. The sources of polystyrene microplastic exposure, degradation pathways, routes of entry into the human body, and target organs for accumulation are presented in FIG. 1.

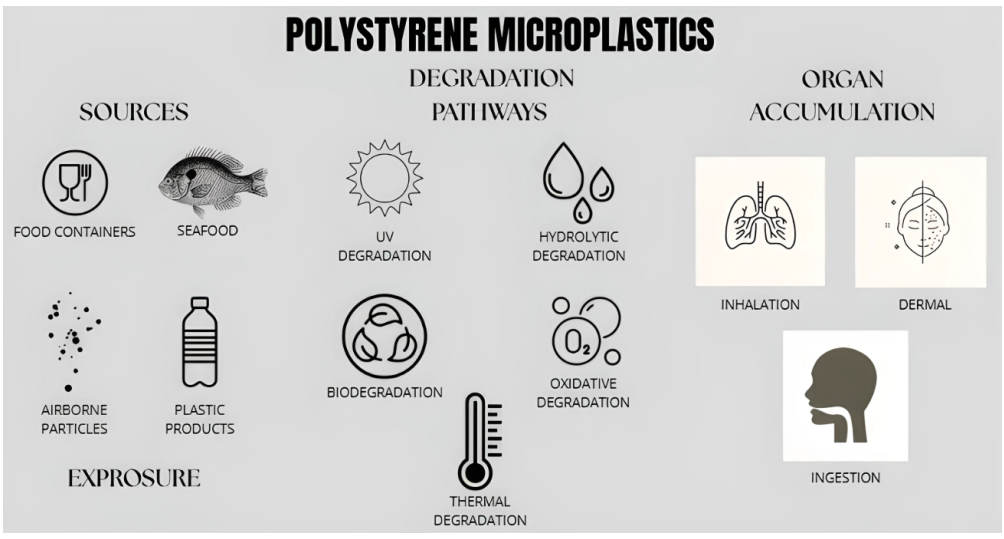

FIG. 1. Polystyrene microplastics: sources, exposure, degradation pathways, and organ accumulation

Analytical Methods for the Detection of PS-MPs

Polystyrene microplastics (PS-MPs) have been increasingly detected in various human tissues, raising concerns about their potential health impacts. Accurate identification and quantification of PS-MPs are essential for understanding exposure levels, biological distribution, and toxicological effects. This chapter offers a comprehensive examination of the prevalent analytical methods employed to detect polystyrene microparticles (PS-MPs) within biological samples. It delves into the underlying principles of these techniques, elucidates their respective advantages, and discusses the limitations associated with each approach.

Spectroscopic Techniques

Fourier-transform infrared spectroscopy (FTIR) is among the most used methods for identifying PS-MPs. It relies on characteristic vibrational modes of chemical bonds, though its detection limit is generally restricted to particles larger than 20 μm [85]. Micro-reflectance FTIR (μ-TR-IR), when combined with multivariate analysis such as principal component analysis (PCA), demonstrates enhanced sensitivity in detecting PS-MP degradation compared to conventional ATR-IR [85], [86].

Raman spectroscopy provides superior spatial resolution (down to 1 μm) and is especially valuable for identifying PS-MPs in complex biological samples. The characteristic peak for PS appears at 1002 cm^{-1} (corresponding to the aromatic ring breathing mode), which is unique to polystyrene compared to PE or PP. This peak is absent in other common microplastics, such as polyethylene (PE) or polypropylene (PP), enabling PS identification even in mixed polymer samples. Raman mapping allows for precise localization and quantification of PS particles ranging from 400 to 2600 nm [80], [87], [88], [89].

Surface-enhanced Raman spectroscopy (SERS) shows promise for detecting PS-MPs at the nanoscale, reaching detection limits as low as 6.5 μg/ml. This method utilizes gold nanoparticles to amplify Raman signals, allowing trace-level analysis [90].

Chromatographic Techniques

Pyrolysis–gas chromatography–mass spectrometry (Py-GC/MS) is considered the most sensitive and specific method for analysing PS-MPs through analysis of characteristic thermal degradation products. It enables both identification and quantification based on characteristic pyrolysis products such as styrene monomers, dimers, and trimers, which result from terminal and random β-scission of the polymer backbone. The optimal pyrolysis temperature for PS is approximately 600°C. These pyrogram signatures are polymer-specific and enable the unambiguous identification of PS even at trace levels. The accuracy of this technique depends on the use of polymer standards, as molecular structure significantly influences pyrolytic efficiency and decomposition profiles. Moreover, co-pyrolysis interactions between different types of microplastics can complicate quantitative analysis [21], [91], [92].

Microscopic Techniques

Fluorescence microscopy using selective dyes is effective for preliminary screening of PS-MPs. Fluorescein exhibits the strongest fluorescence enhancement with PS compared to other polymers, allowing for selective detection in biological matrices. This approach is relatively simple and fast. Scanning electron microscopy (SEM) provides detailed morphological information, such as surface roughness, degradation features, and presence of biofilms on PS particles. When combined with energy-dispersive X-ray spectroscopy (EDX), elemental composition analysis of the particle surface is also possible [88], [93].

Emerging Analytical Techniques

Fluorescently labelled peptide-based mass spectrometry, combined with electrochemical impedance spectroscopy (EIS), offers selective detection of PS-MPs in various water matrices. Detection limits reach 50 ppb in distilled and tap water, and 400 ppb in saline water [94]. Flow cytometry enables rapid particle counting and characterization based on light scattering and fluorescence, which is particularly useful for studying cellular uptake kinetics of PS-MPs [95]. Engineered peptides show specific binding affinity for PS versus other polymers, with up to six-fold higher capacity for PS compared to random DNA sequences [96], [97]. The main analytical techniques used to detect polystyrene microplastics in human tissues are illustrated in FIG. 2.

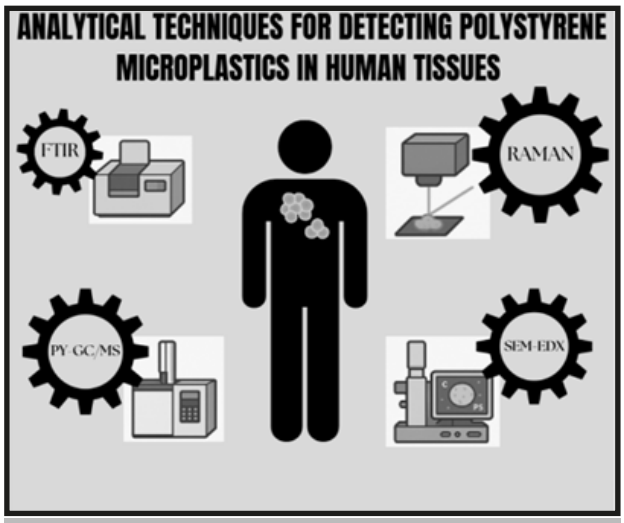

FIG. 2. Analytical techniques for detecting polystyrene microplastics in human tissues

The Impact of Microplastics on Human Health

The build-up of microplastics within the human body has generated substantial concern over the potential implications these might have on health outcomes. Emerging research suggests that microplastics may trigger a range of adverse biological responses, including inflammation, oxidative stress, and endocrine disruption. In response to growing environmental concerns, the European Union implemented Regulation (EU) 2023/2055, effective from 17 October 2023. This regulation restricts the use of synthetic polymer microparticles intentionally added to products, aiming to reduce microplastic emissions and protect the environment. The restriction applies to various products, including cosmetics, detergents, fertilizers, plant protection products, and certain medical devices [98]. The World Health Organization (WHO) has acknowledged the potential risks associated with microplastics and recommends monitoring their presence in drinking water and other environmental media. WHO emphasizes the need for further research to assess the health risks of microplastics and to inform appropriate management actions [99]. This chapter examines the current evidence on the health effects of microplastic exposure, with a focus on both localized and systemic impacts.

Cellular Toxicity Mechanisms

Polystyrene microplastics cause oxidative stress by increasing ROS production and interfering with essential antioxidant enzyme activities. Studies have demonstrated that they inhibit superoxide dismutase (SOD2) and catalase activity in cells exposed to PS-MPs [100], [101]. The resulting oxidative stress damages DNA and protein, potentially initiating carcinogenic pathways [102] The size of PS particles significantly influences the intensity of oxidative stress in mouse hepatocytes [101]. The toxicity mechanisms of PS-MPs also influence the distribution of cellular metabolism and gene expression [67]. Combined exposure to microplastics with other pollutants, such as triphenyl phosphate (TPHP), enhances toxic effects in HepG2 cells [103]. Enzymatic biomarkers indicate a wide spectrum of cellular function disruptions, including acute and chronic exposure effects [104].

Impact on the Respiratory System

Chronic exposure to polystyrene microplastics causes severe pulmonary damage and fibrosis development. Animal studies demonstrate that PS-MPs induce pulmonary fibrosis through activation of the cyclic GMP-AMP synthase (cGAS)/stimulator of interferon genes (STING) signalling pathways and promotion of ferroptosis in alveolar epithelial cells (AECs) [22], [66]. Mechanistically, PS-MPs exposure results in characteristic ferroptosis markers, including significant glutathione (GSH) depletion, increased malondialdehyde (MDA) levels, and iron overload in lung tissue and alveolar epithelial cells [64], [105]. These biochemical changes trigger oxidative stress-mediated cell death pathways that contribute to progressive pulmonary fibrosis [65]. Moreover, the size-dependent effects of polystyrene particles further influence toxicity mechanisms, with nanoscale particles (PS-NPs) causing ferroptosis through ROS-dependent endoplasmic reticulum stress and mitochondrial dysfunction. Ferritinophagy mediated by oxidative stress-driven mitochondrial damage plays a crucial role in PS-NP-induced ferroptosis and subsequent lung injury [106], [107].

Impact on the Reproductive System

Polystyrene microplastics demonstrate specific toxicity to reproductive tissues. Exposure of human placental explants to 5 µm PS-MPs leads to time-dependent cytotoxicity, oxidative stress, and metabolic disruption [70]PS-MPs significantly reduce the activities of key antioxidant enzymes, including catalase, superoxide dismutase (SOD), and peroxidase, in reproductive tissues [108], [109]. Chronic exposure causes testicular toxicity through decreased testosterone levels and impaired spermatogenesis [110], [111]. In the female reproductive system, PS-MPs induce ovarian dysfunction through oxidative stress and apoptosis in ovarian tissues [112]. Gestational exposure results in placental damage and metabolic disorders, disturbing the maternal-fetal immune balance [113], [114].

Carcinogenic Potential

Discovered evidence suggests polystyrene microplastics (PS-MPs) may exhibit carcinogenic properties through metabolic reprogramming mechanisms. In normal human colon cells, PS-MPs induce metabolic rewiring like cancer metabolism, including enhanced glycolysis and increased glutamine utilization to sustain anabolic processes [115], [116]. These metabolic changes in colon cells resemble those induced by carcinogens, raising concerns about long-term exposure effects. PS-MPs activate the Wnt/β-catenin signalling pathway, which plays a crucial role in cancer development [117], [118].

Innovations and Challenges in Microplastic Research

Microplastic research is rapidly evolving, driven by advances in analytical technologies and a growing awareness of environmental and health risks. Despite significant progress, the field continues to face key challenges, including the standardization of methods, the detection of nanoplastics, and the assessment of long-term biological effects.

Standardization of Analytical Methods

One of the major challenges in PS-MP research is the lack of standardized analytical protocols. Variability in sample preparation methods across laboratories significantly hinders cross-study comparability and meta-analyses [25]. The development of certified reference materials and harmonized protocols is urgently needed to establish robust inter-laboratory validation frameworks. Equally important is the engineering of environmentally relevant PS-MP models. Most current studies rely on commercially available polystyrene microspheres, which differ substantially from environmentally weathered particles in terms of morphology, surface oxidation, chemical composition, and adsorbed contaminant profiles [25], [119]. The implementation of controlled weathering protocols that simulate realistic environmental aging processes can significantly improve the ecological relevance and translational value of toxicity studies [25], [120], [121].

Advanced Analytical and Experimental Platforms

Raman mapping holds great promise for high-resolution detection of submicron PS-MPs. Future research should focus on improving detection sensitivity for particles smaller than 1 µm [122]. Microfluidic organ-on-a-chip models, such as gut–liver systems, offer physiologically relevant platforms to investigate the transport and accumulation of PS-MPs under dynamic flow conditions that mimic human physiology [109].

Interdisciplinary Approaches and Biotechnological Solutions

A multidisciplinary framework integrating polymer chemistry, materials science, analytical chemistry, and toxicology is essential for addressing the complexity of PS-MPs. This collaborative effort can lead to the creation of comprehensive reference materials and robust risk assessment tools. Bioengineering microorganisms capable of degrading PS is an emerging strategy. Genetic modification of bacteria to express plastic-degrading enzymes offers potential for bioremediation of PS-contaminated environments [110], [111], [112].

Epidemiological Research and Biomonitoring

Long-term epidemiological studies are necessary to assess the relationship between PS-MP exposure and chronic diseases [126]. These studies should incorporate exposure biomarkers, dose–response assessments, and stratification of vulnerable populations. Effective biomonitoring requires the development of standardized protocols for sample collection, storage, and analysis. Establishing reference values across different age groups and geographical regions is critical for public health assessment.

Biomaterials and Nanotechnology Applications

Biomaterials engineering may support the development of nanodevices, or particles designed to bind and eliminate PS-MPs from biological systems. Similarly, nanomaterials for environmental filtration and detoxification may offer vi-

able solutions for mitigating PS-MP exposure [114], [115]. Bacterial nanorobots programmed to degrade PS-MPs are a futuristic yet promising avenue. Engineered strains, especially those already prevalent in wastewater treatment systems, could be modified to biodegrade polystyrene and other persistent plastics.

Conclusions

Polystyrene microplastics (PS-MPs) represent a growing concern for public health due to their capacity to accumulate in vital organs and elicit a range of toxicological effects. Current evidence confirms the presence of PS-MPs in human blood, lungs, liver, kidneys, brain, and placenta—where they contribute to oxidative stress, metabolic dysfunction, and potentially carcinogenic outcomes. Research into PS-MPs relies on a suite of advanced analytical methods, including Raman spectroscopy, FTIR, pyrolysis-GC/MS, and fluorescence microscopy. While each technique offers unique strengths, their combined application through a multi-analytical approach is essential for comprehensive detection and characterization. Looking forward, there is a pressing need for standardization of analytical protocols, the development of environmentally relevant PS-MP models, and long-term epidemiological studies to better understand human exposure and associated health risks. Interdisciplinary collaboration—spanning biomaterials engineering, nanotechnology, and bioengineering—will be crucial to advancing effective prevention and remediation strategies. Given the widespread presence and persistence of microplastics, addressing the challenges posed by PS-MPs is of broad scientific, environmental, and societal importance. The development of innovative materials and technologies for the detection, removal, and degradation of microplastics has the potential to significantly enhance public health protection and environmental sustainability.

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