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REVIEW ARTICLE

Polytetrafluoroethylene microplastic properties, pollution, toxicity and analysis: a review

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Abstract

Cooking with polytetrafluoroethylene-coated pans releases thousands to millions of microplastic and nanoplastic particles per use, directly contaminating food and the environment. Here we review polytetrafluoroethylene microplastics with emphasis on polytetrafluoroethylene characteristics, environmental occurrence, and detection methods. Polytetrafluoroethylene has high chemical stability and is used in medical devices, clothes and protective suits, aerospace, non-sticking pans, cables and insulation, filtration, irrigation and electronics. We discuss plastic utensils as microplastic sources, and the influence of temperature and aging on microplastic release. The presence of microplastics in humans, wild animals, sediments, water and the atmosphere is described. Limitations of actual analytical methods such as density separation are detailed. Polytetrafluoroethylene accounts for about 60% of the global fluoropolymer market, and is a major contributor to microplastic pollution, accounting for up to 44% of microplastics in sediments, 74% in benthic fish, and 60% in human organs. Our meta-analysis shows that polytetrafluoroethylene microplastic concentrations average 7.3 ± 13.3 particles per L in water, 3,685.7 ± 4,832.0 particles per kg in sediment, 24.9 ± 37.1 particles per individual in fish, and 482.5 ± 554.1 particles per kg in human tissues. Polytetrafluoroethylene microplastics may impair physiological homeostasis by inducing oxidative stress, inflammation, necrosis, and disruption of key cellular signaling pathways.

Keywords Polytetrafluoroethylene · Microplastics · Nanoplastics · Synthesis · Production · Applications · Detection methods · Environmental occurrence · Persistence · Release conditions · Toxicological profile · Exposure routes · Human exposure · Risk assessment

Introduction

Microplastics are widespread environmental contaminants detected across various matrices, including air, food, water, salt, indoor dust, and beverages, leading to a continuous increase human exposure [1–6]. Evidence of systemic bioavailability is growing, as microplastics have been identified in human tissues, organs, body fluids, and excreta, raising serious concerns about potential long-term health risks [7–14]. Health effects associated with microplastic exposure include inflammation, oxidative stress, and apoptosis, along with organ-specific impacts such as intestinal disruption and fibrosis in the kidneys and heart [15–19]. Reproductive toxicity is among the most alarming outcomes [20–24]. Additionally, emerging evidence implicates microplastic exposure in metabolic dysfunction and the activation of carcinogenic pathways [25–28]. These findings highlight the urgent need to identify key sources of microplastic exposure in daily life and to better understand their potential health effects.

Although environmental degradation generates microplastics over centuries, direct release can occur within seconds during daily plastic use, for example, infant feeding bottles may release thousands of particles during open–close cycles, and kitchen blenders can emit billions of particles in just few seconds [29–33]. Other significant sources include food containers, take-out packaging, and even teabags composed of biodegradable polymers [34, 35]. Plastic cutting

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boards alone can generate tens of grams of microplastics annually [36]. Utensils made from polymers such as polyethylene, polypropylene, polystyrene, and polyvinyl alcohol have been shown to release from tens to thousands of particles per Liter, depending on material composition and use conditions [37, 38]. Environmental stressors, including heat, mechanical agitation, and prolonged storage, further accelerate microplastic release. Notably, microwave heating or exposure to hot water can trigger the release of billions of particles from a single plastic item [39, 40]. These findings highlight the importance of evaluating microplastic emissions from everyday food- and beverage-contact materials, as they represent a direct and often overlooked route of human exposure.

Polytetrafluoroethylene (PTFE) is valued for its thermal stability, chemical resistance, and low surface energy, making it widely used in cookware and industrial applications [41–45]. Historically considered inert and non-leaching [46–49], recent studies have shown that PTFE can degrade under heat, abrasion, and chemical exposure, releasing micro- and nanoplastics [50–54]. Notably, everyday cooking with PTFE-coated utensils can produce millions of these particles, especially as cookware ages [55–58]. PTFE microplastics have been detected in human placenta, lungs, and urine, suggesting widespread exposure [59–61]. Although PTFE is classified as an agent included in the Group 3 of carcinogenic risk, its health and environmental risks remain poorly understood due to fragmented data and limited reviews [53, 62, 63]. This review addresses these gaps by assessing properties, uses, release mechanisms of PTFE, and occurrence in environmental and biological systems, while also highlighting analytical challenges and future research needs. Moreover, we performed a meta-analysis to provide a standardized, quantitative assessment of PTFE occurrence across environmental matrices, wildlife, and humans, enabling clearer comparisons, trend identification, and risk evaluation.

Plastic utensils as direct sources of microplastics

The migration of microplastics from plastic food packaging presents an emerging food safety concern that remains insufficiently addressed by current United States Food and Drug Administration (US FDA) regulations for food-contact substances [64]. Plastic containers can release microplastics into food and drinks, especially under high-temperature conditions during use or cleaning (Fig. 1; Table 1) [54, 65]. Such contamination during food handling and preparation

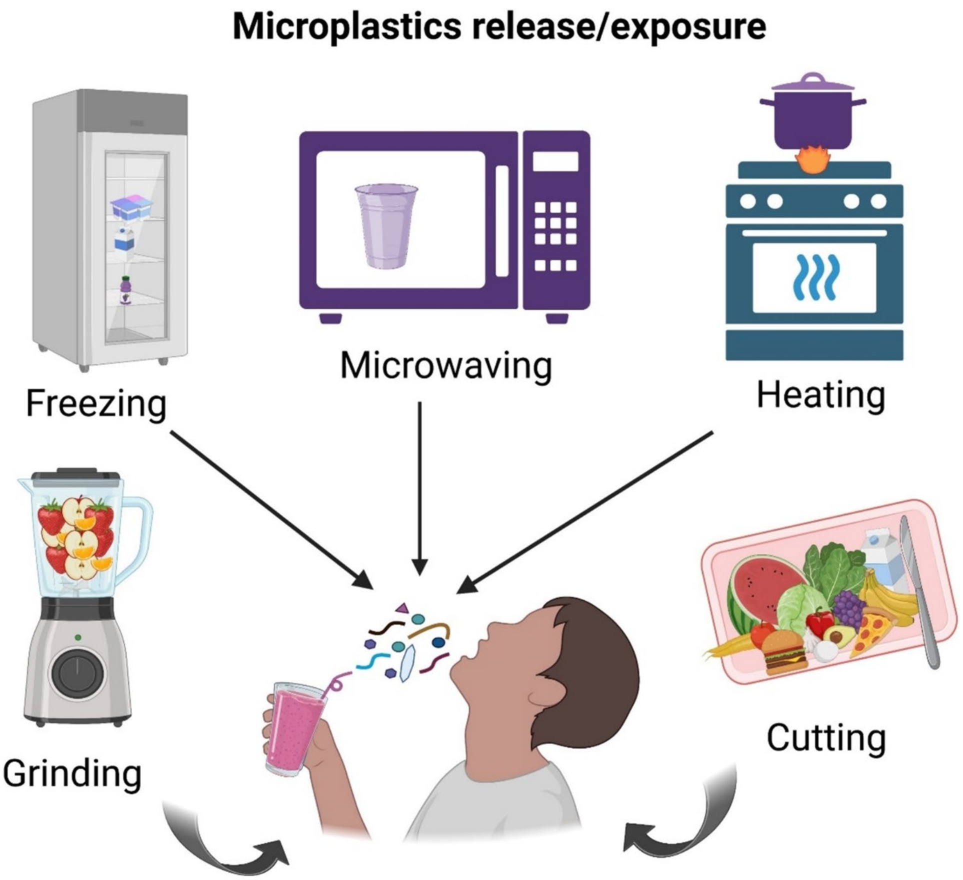

Fig. 1 Microplastic release during household processing using plastic utensils. Common household activities, including freezing, microwaving, heating, grinding, and cutting, can induce microplastic release from plastic utensils such as cutting boards and containers. These microplastics may contaminate food and beverages, contributing to human exposure and raising potential health concerns

Table 1 Microplastic release from various plastic objects is influenced by the polymer type and daily use conditions, such as temperature, stress, and solvent exposure

Plastic object	Daily use conditions	Plastic polymers	Detection method	Concentration	Size	References
Feeding bottles and water bottles	During 100 opening/closing cycles	Polycarbonate, polypropylene and polyphenylene sulfone resins	LDIR and FTIR	53–393 × 10^3 particles/L	20–500 µm	[32]
Various plastic container	Kitchen blender to make juice for 30 s from various plastic containers	Polystyrene, polyethylene terephthalate, polyethylene, polyvinyl chloride, polypropylene, polyamide, poly methyl methacrylate, polycarbonate, polyurethane, acrylonitrile butadiene and styrene	Raman spectroscopy	0.36–0.78 × 10^9 particles/container	–	[33]
Take-out containers	Direct flushing and flushing after immersing with hot water	Polypropylene, polystyrene, polyethylene and polyethylene terephthalate	FTIR	3–29 particles/container	lower than 500 µm	[34]
Tea bags	During preparing one teacup	Polylactic acid	FTIR	~ 1 × 10^6 particles/tea bag	200 – 400 nm	[35]
Chopping board	During chopping on plastic boards	Polyethylene and polypropylene	FTIR	7.4–50.79 g or 14.5–71.9 × 10^6 (polyethylene) and 49.5 g or 79.4 × 10^6 (polypropylene) particles/person/year	lower than 100 µm	[36]
Disposable cups (90 batches)	Containing pure water at 95 °C for 20 min	Polyethylene, polypropylene and polystyrene	Raman spectroscopy, SEM and AFM	0.7–6 × 10^3 particles/L	lower than 20 µm	[37]
Packaged food ice cubes (fifteen most popular commercial brands)	Contacting take-out food with disposable plastic containers	Polypropylene, polyethylene, polyvinyl alcohol, tygon polymer, sealing ring gardena 2824 large, polyamide 6, and cellophane	FTIR	19 ± 4–178 ± 78 particles/L	lower than 300 µm	[38]
Packaging, cups, transparent boxes, and expandable boxes	Soaking in hot water (100 °C) for 60 min with agitation	Polyethylene, polypropylene and polystyrene	FTIR	1.07–2.24 × 10^9 particles/L	1–5,000 µm	[39]
Food containers	Microwave heating (3 min, room temperature or refrigeration storage (six months)	Polyethylene and polypropylene	Raman spectroscopy	4.22 × 10^6 and 1.21 × 10^9 of microplastics and nanoplastics/cm^2	1 – 14 µm	[40]
Take-out food	Contacting take-out food with disposable plastic containers	Polyethylene	Raman spectroscopy	639 particles/kg	lower than 500 µm	[56]
Water and food containers	Containers treated using distilled water and food stimulants (10% and 50% ethanol) under various conditions	Polypropylene, polyethylene terephthalate, and polystyrene	Raman microscopy	23.7–490.3 × 10^3 particles/L	lower than 5 µm	[64]
Food and drink containers in eat-in and takeaway catering	Exposure of containers to hot water (95 °C) or ice-cold water for 1 or 5 h	Polypropylene, polystyrene, and high-density polyethylene	FTIR	10–710 particles/L	25 – 30 µm	[65]

Table 1 (continued)

Plastic object	Daily use conditions	Plastic polymers	Detection method	Concentration	Size	References
Silicone-rubber baby bottle teats for infant feeding	New teats were steamed for 10 min at 100 °C, rinsed with deionized water, and air-dried	Silicon and rubber	FTIR	more than 0.66×10^6 particles/infant	lower than 10 µm	[69]
Takeaway containers	Containers treated with Milli-Q water at room temperature, 100 °C, and at pH 4.5 for 20 min with agitation	Polypropylene, polystyrene, and polyethylene terephthalate	Raman spectroscopy	9, 17, and 7 (polyethylene terephthalate) and 1, 30 and 3 particles/container (polystyrene) at 0 °C, pH 4.5 and 100 °C, respectively	13–32 µm	[70]
Infant feeding bottles	Food preparation and storage	Polypropylene	–	16.2×10^6 particles/L	–	[73]
Single-use cups	Cups kept at 4, 50 and 80 °C for 0, 5, 10 and 20 min	Polypropylene, polystyrene and polyethylene	FTIR	$0.13–1.4\times10^3$ particles/L	0–50 µm	[74]
Disposable drink cups	The residence time of the drink in the cup, shaking, and water temperatures	Polypropylene, polyethylene terephthalate and polyethylene	–	$0.7–1.5\times10^3$ particles/cup after 5 min exposure	lower than 50 µm	[75]
Plastic food containers	Plastic containers filled with 100 mL of Milli-Q water were stored at − 20 °C and 4 °C for 24 h prior microwave heating	Polypropylene, and polystyrene	SEM and FTIR	100– 260×10^3 particles after extraction (Equivalent to 0.1 and 0.3 mg of each container)	0.18–0.32 µm	[76]
Plastic teabags	Steeping a single plastic teabag at brewing temperature (95 °C)	Nylon and polyethylene terephthalate	FTIR and XPS	11.6×10^9 (more than 1 µm) and 3.1×10^9 (lower than 1 µm) per a single cup of the beverage	more and lower than 1 µm	[77]
Plastic containers and reusable food Pouches	Microwave-safe baby food containers heated by microwave and water bath at the same heating rates	Polypropylene	Py-GC/MS	~10^7 particles/cm^2 (nanoplastics) and ~10^6 particles/cm^2 (microplastics). Higher temperatures generated more microplastics	–	[78]
Takeaway food containers	Two thermal usages, including hot water and microwave treatments	Polystyrene, polypropylene, polyethylene terephthalate and polylactic acid	TEM and DLS	$285.7\times10^3–681.5\times10^3$ particles/cm^2 in containers (thermal treatment 95 °C). showed lower values ranging from $171.9\times10^3–301.6\times10^3$ particles/cm^2 (microwave treatment)	50–200 µm	[79]
Four brands of self-heating food packaging	The food subject to exothermic reaction, followed by filtration after 1 h	Polypropylene	Raman spectroscopy	2.36×10^6 particles/L	lower than 20 µm	[80]

Analytical techniques, including Fourier transform infrared spectroscopy (FTIR), scanning electron microscopy (SEM), atomic force microscopy (AFM), pyrolysis–gas chromatography/mass spectrometry (Py-GC/MS), transmission electron microscopy (TEM), laser direct infrared imaging system (LDIR), dynamic light scattering (DLS), and X-ray photoelectron spectroscopy (XPS), are used to detect the released microplastics. To ensure consistency, concentrations are standardized to per kilogram for solid matrices and per Liter for liquid matrices constitutes a major dietary exposure route. Estimated annual ingestion ranges from 39×10^3 to 52×10^3 particles per person, increasing to 74×10^3–121×10^3 particles when inhalation is included. Bottled water alone may contribute up to 90×10^3 particles annually, compared to approximately 4×10^3 from tap water [66]. Microplastic exposure is amplified by the diversity of intake sources and tends to accumulate over time. Average daily exposure per person is estimated at 382 ± 205 particles from drinking water, 594 ± 269 from air, and 1,036 ± 493 from food [67]. Although estimates vary across studies, ingestion and inhalation consistently emerge as the primary exposure routes, with plastic packaging, utensils, and storage containers identified as major contributors [7, 36, 66, 68]. Accurately measuring micro- and nanoplastics in environmental and biological samples is challenging due to the absence of standardized protocols, leading to inconsistent and unreliable data across studies.

Food containers as primary sources

Over the past decade, accumulating evidence has identified household food-contact materials as significant contributors to microplastic exposure. Initial studies revealed that feeding and water bottles made from polycarbonate, polypropylene, and polyphenylene sulfone resins could release between 53×10^3 and 393×10^3 microplastic particles per Liter, after only 100 opening and closing cycles [32]. Subsequent research extended these findings to prepared foods, demonstrating that both homemade and takeaway meals may contain microplastics, with concentrations ranging from 3 to 29 particles per container and up to 639 particles per kilogram in take-out dishes [34, 56]. Recent studies have found that household appliances like plastic kitchen blenders can release large amounts of microplastics, about $0.36–0.78 \times 10^9$ particles in just 30 s of use due to mechanical stress [33]. In both dine-in and takeaway settings, food and beverage containers made from polypropylene, polystyrene, and high-density polyethylene have been reported to release between 10 and 710 particles per Liter, depending on the container type and usage conditions [56]. Packaging materials also contribute significantly to microplastic release.

Plastic cups, transparent boxes, and expandable food containers have been shown to emit between 1.07×10^9 and 2.24×10^9 particles per Liter [39]. In addition, everyday kitchen tools such as cutting boards represent notable sources of contamination. Polyethylene cutting boards were estimated to release 7.4–50.79 g ($14.5–71.9 \times 10^6$ particles) annually, while polypropylene boards contributed approximately 49.5 g (79.4×10^6 particles) [36]. Silicone-rubber products like baking molds, collapsible kettles, and sealing rings release microplastics when heated to temperatures of 100 °C or higher, increasing the risk of dietary microplastic exposure [69]. Table 1 and Fig. 1 provide a comprehensive overview of microplastic release from various household utensils during typical food preparation and storage processes, highlighting the diverse sources contributing to direct human exposure.

Polymer type and usage influence microplastic release

Microplastics have been detected leaching from nearly all commonly used food-contact polymers, with release levels strongly influenced by polymer type, usage conditions, and product design. Broad-spectrum evaluations have shown that containers made from polypropylene, polyethylene, polyvinyl alcohol, polyamide 6, Tygon polymer, and cellophane consistently release microplastics across all tested samples, with concentrations ranging from 19 ± 4 to 178 ± 78 particles per Liter [38]. Comparative analyses of disposable cups exposed to hot water (95 °C for 20 min) revealed similar magnitudes of microplastic release among various polymers: polyethylene (675–5984 particles/L), polypropylene (781–4951 particles/L), and polystyrene (838–5215 particles/L) [37]. These findings underscore the difficulty of designating any polymer as universally "safer" in terms of microplastic shedding.

Biodegradable plastics, often marketed as environmentally friendly alternatives to conventional petroleum-based polymers, do not necessarily reduce microplastic release. For instance, teabags manufactured from biodegradable materials were found to release up to one million particles per use [35]. Moreover, the assumption that certain polymers are inherently safer has been challenged. Although some studies reported no detectable microplastic release from polypropylene under certain conditions comparable to polyethylene terephthalate and polystyrene, others found that it released the highest levels of microplastics when exposed to 50% ethanol at 130 °C for 15 min [64, 70].

Although petroleum-derived thermoplastics such as polyethylene terephthalate and nylon have been the primary focus of microplastic studies, emerging evidence suggests that elastomeric materials like silicone rubber also contribute to microplastic exposure, particularly under high-temperature usage scenarios [69, 71, 72]. Polymer type and usage conditions, such as temperature, solvent exposure, and mechanical stress, are key factors influencing microplastic release, which in turn affects human exposure and health risks.

Human microplastic exposure from food and consumer products

Recent evidence indicates that human exposure to microplastics via food and beverage consumption is both widespread and significant, varying according to age, behavior, and product use. Individuals who consume takeaway meals 4–7 times per week may ingest between 12 and 203 microplastic particles per meal [34], translating to an estimated 195×10^3 particles annually through food and beverage storage alone [65]. Even occasional takeaway consumption (1–2 times per week) may result in the ingestion of 170–638 particles weekly [56]. Infants face particularly high exposure levels. Polypropylene feeding bottles can release up to 16.2×10^6 microplastic particles per Liter, contributing to estimated daily intakes ranging from 14.6×10^3 to 4.55×10^6 particles per infant worldwide [73]. In addition, silicone-rubber baby teats may lead to ingestion of over 0.66 million particles by a one-year-old child annually, with global emissions from teats disinfection reaching 5.2×10^{13} particles per year [69].

Microplastics are also released from routine household items. Chopping boards made from polyethylene can contribute $14.5–71.9 \times 10^6$ particles per person annually [36]. In Mexico City, ice consumption alone was linked to the ingestion of $4.9 \pm 3.4 \times 10^2$ to $1 \pm 0.7 \times 10^4$ particles per year [38]. Disposable drinking cups further add to the burden, potentially contributing between 18.7×10^3 and 73.8×10^3 particles annually through hot and cold beverage intake [74]. Overall, average adult ingestion is estimated at 39×10^3 to 52×10^3 particles per year from food and beverages, with inhalation further increasing cumulative exposure [66]. Some models suggest inhalation could contribute up to 4.5×10^3 particles per kilogram of body weight per day [64]. Additionally, infants consuming microwaved water from polypropylene containers may ingest up to 20.3 ng/kg/day, while toddlers consuming microwaved dairy products may reach 22.1 ng/kg/day [40]. These findings underscore the pervasive nature of direct microplastic exposure from consumer products and household utensils. In this context, PTFE-based utensils represent a potentially significant but underexplored source of microplastic release, meriting systematic investigation.

Polytetrafluoroethylene

Properties

Fluoropolymers, including PTFE, polyvinylidene fluoride, and polyvinyl fluoride, play a critical role in diverse industrial applications. Among them, PTFE stands out due to its exceptional chemical resistance, thermal stability, and low flammability [81, 82]. PTFE was first synthesized in 1938 by Roy J. Plunkett, who discovered the polymerization of tetrafluoroethylene into a solid form exhibiting non-stick and chemically inert characteristics [83]. Tetrafluoroethylene (C_2F_4) is a colorless, gaseous compound with a molecular weight of 100.02 g/mol, a density of 1.52 g/cm^3, and a boiling point of –76.3 °C. It is insoluble in water and capable of forming explosive peroxides upon air exposure.

PTFE, also known by the trade name Teflon™, is a high-molecular-weight, semi-crystalline thermoplastic composed of repeating C_2F_4 units. Its structure is dominated by strong carbon–fluorine (C–F) bonds, which confer a suite of valuable properties: chemical inertness, hydrophobicity, low surface energy, and resistance to thermal, biological, and oxidative degradation. PTFE exhibits an exceptionally low coefficient of friction (0.05–0.1) and outstanding wear resistance, earning it the moniker "the king of plastics" [46, 84, 85]. It falls under recycling code 7, reflecting its classification outside the standard categories. Although PTFE has an impressive melting point of ~ 327 °C and excellent thermal resilience, it may begin to degrade at slightly lower temperatures, raising concerns about microplastic generation under typical usage conditions [86]. Figure 2 summarizes core physical and chemical properties of PTFE.

PTFE is one of the densest plastics, with a density of approximately 2.2 g/cm^3, and its high mechanical strength contributes to its widespread versatility across various industrial and consumer applications [87]. It is typically synthesized via the free-radical polymerization of tetrafluoroethylene, although alternative methods—such as hybrid carbon dioxide/aqueous processes—can yield comparable material properties [88]. While PTFE is generally insoluble in most solvents, it can dissolve in select perfluorocarbons and aromatic perfluorocarbons, with solubility dependent on temperature and solvent polarity [89]. PTFE's exceptional chemical inertness and resistance to both acidic and organic solvents [90], make it a material of choice for demanding environments. It is extensively employed in non-stick cookware, food-contact surfaces, protective coatings, electrical insulation, lubricants, bearing components, and medical devices [91]. Its inherently low coefficient of friction, superior wear resistance, and hydrophobic surface further enhance its non-stick performance, solidifying its role across a wide spectrum of industrial applications [92]. In addition to its mechanical and chemical resilience, PTFE holds relevance in optical instrumentation due to its high reflectivity and capacity to diffusely scatter light. It performs consistently well across a broad spectral range, from ultraviolet to near-infrared, thereby contributing to its utility in specialized technological applications [93]. Collectively, these

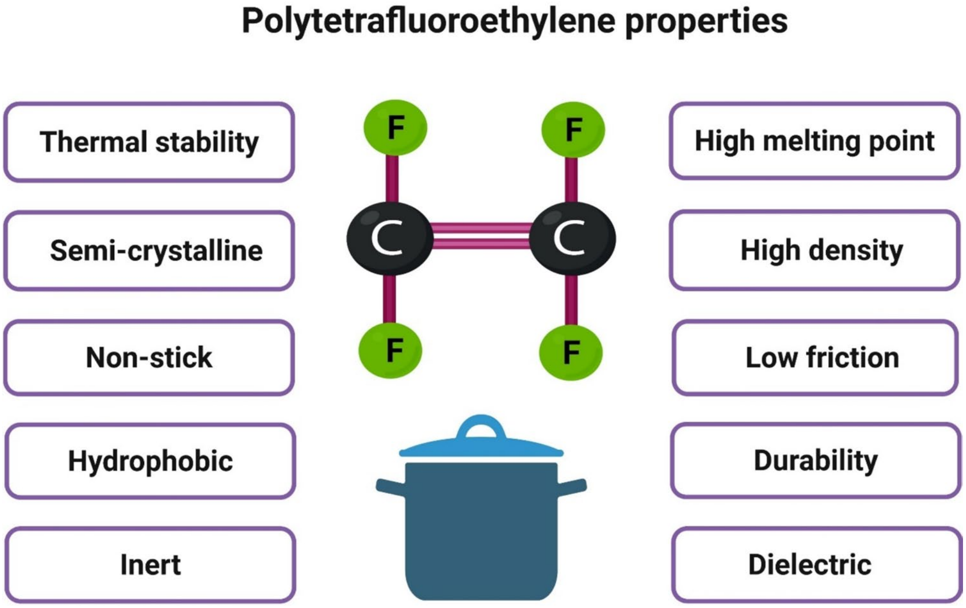

Fig. 2 Key characteristics of polytetrafluoroethylene. Polytetrafluoroethylene exhibits a unique combination of physical and chemical properties, including high density, thermal stability, a semi-crystalline structure, excellent dielectric performance, low friction, hydrophobicity, and a high melting point. These attributes contribute to its exceptional durability and broad applicability across industrial sectors and household utensils

characteristics emphasize PTFE's indispensable role in modern engineering, consumer goods, and high-performance environments.

Applications and production

PTFE, a homopolymer of tetrafluoroethylene, accounts for approximately 60% of the global fluoropolymer market, making it the most widely utilized fluoropolymer worldwide [94]. Its remarkable physical and chemical properties, such as exceptional thermal stability, toughness at low temperatures, low thermal conductivity, excellent dielectric performance, and outstanding chemical resistance (Fig. 2) render it highly suitable for diverse industrial applications [95–97]. The chemical inertness and high molecular weight of PTFE, combined with its availability in various forms (including powders, granules, resins, pastes, and emulsions), enable its widespread use across sectors such as automotive, aerospace, food processing, petrochemicals, and biomedicine [89, 98–100]. Figure 3 illustrates the diverse and expanding applications of PTFE across multiple sectors.

Its durability and porous membrane structure make PTFE particularly effective in filtration technologies, including vapor permeation, ultrafiltration, pervaporation, liquid transport, and chemical purification, where maintaining sample purity and achieving an increase in filtration efficiency are essential [101, 102]. PTFE is also indispensable in applications requiring robust separation performance and chemical stability, such as desalination, industrial wastewater recycling, and air filtration systems [103]. Furthermore, its high thermal resilience, low coefficient of friction, and excellent insulating capabilities support its use in mechanical and electrical components including bearings, gears, non-stick coatings, cable insulation, electrets, and printed circuit boards [104].

In advanced manufacturing, PTFE serves a critical role in protecting sensitive electronic components and facilitating semiconductor production. It is also widely used in gaskets, vessel linings, and high-temperature parts for the automotive and aerospace industries [105]. Its inherently low surface energy provides superior hydrophobicity, while engineered superhydrophobic PTFE surfaces enhance barrier performance and durability [89]. The polymer's lubricity further supports its role in tribological applications [106], and its mechanical strength can be augmented through filler reinforcement for use in high-performance mechanical systems [107]. Additionally, the incorporation of nano-PTFE additives has been shown to result in higher efficiency and longevity of lubricants [108].

As an insulating material, PTFE plays a critical role in electrical transmission systems, electrostatic transducers, and scanning electron microscopy [109, 110]. Its dielectric performance can be further enhanced by modifying PTFE with inorganic fillers or fluoride-functionalized glass fibers, making it highly suitable for high-performance microwave substrates [111]. PTFE also plays a significant role in defence technologies, such as marine coatings, aircraft seals, and weapons systems, where it contributes to an increase in durability and performance. [89, 112].

Due to its bio-inertness and excellent biocompatibility, PTFE is ideal for composite coatings in both the food industry and biomedical applications [113–115]. In food processing, it is valued for its chemical resistance, ability to withstand alkaline and acidic cleaning cycles, and superior aging resistance compared to rubber gaskets [116]. Its chemical stability and non-reactivity with organic substances further

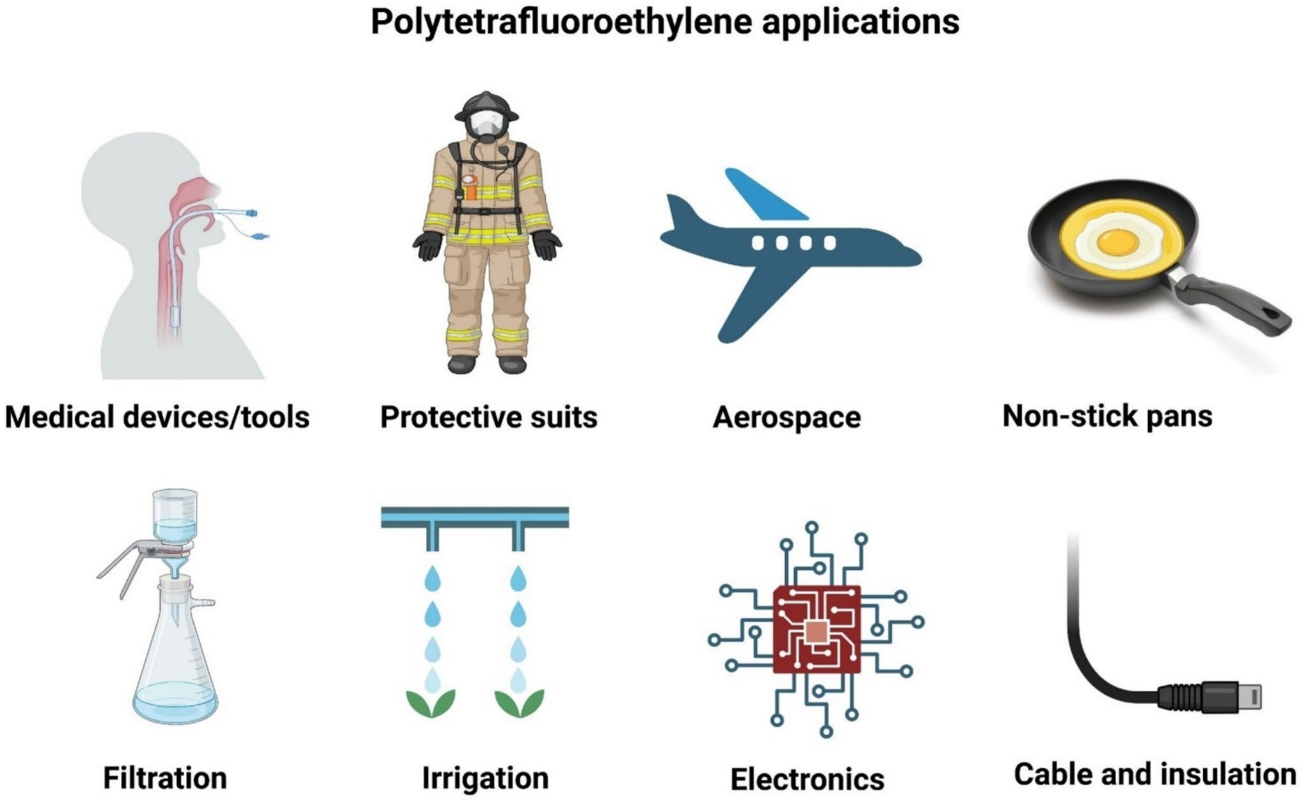

Fig. 3 Versatile applications of polytetrafluoroethylene. Its exceptional thermal resistance, chemical inertness, low friction, and non-stick properties make it suitable for a broad range of structural and functional uses. It is widely applied in insulation, lubrication, protective coatings, and sealing systems across aerospace, automotive, and industrial sectors. In household settings, its non-reactivity and thermal stability make it ideal for non-stick cookware and other kitchen utensil

support its use in biomedical and pharmaceutical contexts, offering higher safety and compatibility [117]. Recent advancements include PTFE-based nanocomposites, such as Ag-Au/PTFE coatings, which exhibit improved antibacterial properties [118]. The healthcare sector continues to drive demand for PTFE due to its inert nature and compatibility with human tissues, leading to its integration in implants, stents, cosmetics, and various medical devices [119, 120]. The widespread industrial and consumer adoption of PTFE has fuelled its large-scale production and cemented its position as the dominant fluoropolymer in the global market. This dominance is largely attributable to its exceptional physicochemical properties and versatility.

As of 2023, granular PTFE accounted for approximately 31.7% of global fluoropolymer market revenue, largely due to its use in high-performance applications [89]. Fine-powder PTFE, favored for coatings, lubricants, and mechanical components due to its self-lubricating nature, is projected to grow at a compound annual growth rate (CAGR) of 6.3% [105]. The global PTFE market was valued at US dollars (USD) 2.8 billion in 2024 and is forecasted to reach USD 3.5 billion by 2029, reflecting a CAGR of 4.3% [121]. In production terms, global demand for PTFE ranged from 110,000 to 190,000 metric tons in 2022, representing over 50% of total fluoropolymer consumption. This demand is expected to rise to approximately 250,000 metric tons by 2026, with a projected CAGR of 5% between 2021 and 2026 [91, 122, 123]. China remains the world's leading PTFE producer, accounting for over 50% of global production capacity and more than 40% of global demand as of 2022 [91].

Despite wide-ranging utility and economic value of PTFE, it also poses notable occupational and environmental health concerns. Inhalation of PTFE particles has been linked to acute pulmonary toxicity; however, the chronic effects of long-term exposure remain inadequately studied and warrant further research [124]. Beyond occupational hazards, environmental persistence adds another layer of concern of PTFE. Its extensive presence in medical devices and consumer products, especially non-stick cookware and plastic food containers, has led to the detection of PTFE microplastics in human tissues, indicating possible exposure through ingestion, inhalation, and dermal contact [60, 125, 126]. These findings underscore the pressing need for comprehensive data on PTFE microplastic release, with particular attention to the increasing environmental distribution and higher potential for human exposure pathways.

Polytetrafluoroethylene release from plastics products

A growing food safety concern involves the migration of microplastics from plastic packaging and utensils during food production, storage, and handling. Particular attention has been given to plastic bottles, microwaveable containers, and baby bottles, which are especially prone to microplastic release under high-temperature conditions [54]. Cookware and other food-contact materials are composed of diverse substances, including metals, ceramics, glass, and plastics, among which PTFE-coated non-stick pans are especially prevalent [46]. While PTFE offers notable benefits, including ease of use and non-stick functionality, its safety has come under increasing scrutiny over the past decade due to potential health risks associated with its degradation [48]. Recent studies have shown that both new and aged PTFE-based plastic cookware release microplastics with daily use [57]. Usage conditions significantly influence microplastic release, with variables such as cooking methods and container types contributing to particle migration into food. It is estimated that consuming food 1–2 times per week from plastic containers may lead to the ingestion of approximately 170–638 microplastic particles weekly [56].

PTFE coatings, widely used in household cookware for their non-stick properties, are a significant source of microplastic contamination [50]. Studies using jelly as a food simulant found that plastic cookware, regardless of its age, released between 2409 and 4964 microplastic particles annually, including PTFE, polyethylene, and polypropylene particles ranging from 13 to 318 µm in size. In contrast, non-plastic cookware released no detectable microplastics, emphasizing the potential for contamination in home-cooked meals and raising health concerns [57]. In simulated cooking scenarios lasting only 30 s, scanning electron microscopy revealed the release of millions of PTFE micro- and nanoplastics, up to approximately 2.3 million particles. Damaged surfaces of PTFE-based utensils showed significant particle shedding, with an estimated 9,100 particles released from a single scratch [55]. In addition to those released into food, many particles remain adhered to the pan or cooking utensil itself, suggesting a persistent risk of ingestion. This is particularly concerning given that PTFE belongs to the family of per- and polyfluoroalkyl substances (PFAS), a group associated with environmental persistence and potential toxicity [55]. Furthermore, PTFE-based cookware may emit toxic gases and chemicals even at standard cooking temperatures, and the incorporation of perfluorooctanoic acid (PFOA) during PTFE synthesis adds to health concerns. Despite these risks, there remains a lack of comprehensive data on the toxicity and biological fate of ingested PTFE particles, underscoring the urgent need for further investigation [48].

Effect of temperature on polytetrafluoroethylene release

Microplastic release is significantly influenced by factors such as polymer type, usage conditions, and environmental or operational parameters. For example, disposable drink cups made of polymers like polypropylene, polyethylene terephthalate, and polyethylene released approximately 723–1,489 microplastic particles per cup (or 1808–3723 particles per Liter) when exposed to hot water at 60 °C for 30 min, simulating typical daily use [75]. Elevated temperatures accelerate the release of microplastics and the leaching of chemical additives. Triclosan, an antimicrobial agent, has been detected in water and ethanol stored in polypropylene containers after heating, underscoring temperature's impact on chemical migration [127]. Plastic cookware can reach temperatures of 61–121 °C and even exceed 200 °C in localized hotspots during microwave or oven use, promoting the migration of monomers, oligomers, aromatic compounds, and plasticizers into food [128, 129]. Prolonged heating further intensifies this migration [74].

Although earlier studies reported no definitive migration of perfluorochemicals from PTFE-coated cookware into food simulants [130], recent findings reveal that PTFE utensils release both particles and gases when exposed to high heat. PTFE-coated pans, when heated on a stovetop for 30 min without food, can reach 250–370 °C, temperatures sufficient to degrade the coating and emit per- and polyfluoroalkyl substances (PFASs) [48, 131, 132]. At 486 °C, PTFE degradation produces airborne nanoparticles [133]. These emissions result from increased diffusion rates at elevated temperatures, which enhance contaminant transfer from the polymer matrix into food [134, 135]. Such emissions pose dual risks: direct human exposure and environmental contamination through wastewater discharge. per- and polyfluoroalkyl substances PFASs are particularly concerning due to their persistence and links to toxicity, cancer, and chronic diseases in both humans and animals [81, 136, 137]. Additionally, aging and mechanical wear contribute to heavy metal leaching, such as aluminum, arsenic, cadmium, and lead, especially during extended boiling (1–4 h) in plastic kettles or PTFE cookware [138]. Microplastic release also occurs rapidly during the decomposition of kitchen waste, with temperature and acidity as key drivers, underscoring the need for early waste management strategies [139]. Overall, temperature is a critical factor in the release of microplastics and hazardous substances from PTFE-based utensils, impacting both human health and environmental safety.

Effect of aging

Aging plays a significant role in the release of microplastics from PTFE-coated products. Although aged PTFE-coated cookware may not show visible macroscopic degradation, microscopic surface alterations, such as wrinkling and ridge formation, indicate plastic deformation caused by repeated heating. Life-tested samples have shown early signs of fouling and crazing, with damage resulting from both thermal exposure and mechanical cleaning, both of which can contribute to microplastic release [49, 55, 57, 92, 127]. Studies have found that cooking with PTFE-coated non-stick pans, even when using non-abrasive utensils, can result in the release of PTFE particles ranging from 5 to 227 µm. New utensils released an average of 2.2 ± 0.4 particles per use, while older utensils released nearly twice as many (4.6 ± 1.5 particles) [57]. After approximately two years of typical household use, non-stick pans were found to release 1.2–3.7 times more microplastics from damaged coatings and 1.9–6.2 times more from scratched surfaces [55]. As plastic materials age, molecular chain degradation reduces their elasticity and increases brittleness, which further promotes microplastic release [140]. Damage to PTFE coatings in older cookware may also increase the leaching of heavy metals compared to newer products [138]. Microscopy investigations have confirmed that surface degradation, such as cracks, crazing, and scratches, significantly contributes to increased PTFE microplastic shedding in aged cookware [57, 141]. Overall, aging is recognized as a primary factor driving microplastic release from cooking utensils, regardless of polymer type. This is supported by evidence of elevated carbonyl indices, which reflect greater photochemical degradation in polyethylene and polypropylene particles from older plastic cookware [57]. However, the extent of microplastic leaching due to aging is also influenced by user behavior, including frequency of use and cleaning methods.

Food utensils and condition of uses

Mechanical abrasion during food preparation is a major contributor to the release of microplastics (lower than 5 mm) and nanoplastics (lower than 1 µm) from PTFE-coated cookware [142]. In simulated cooking experiments, dry-mixing with hard utensils, such as stainless-steel spoons, for just 30 s was sufficient to scratch PTFE-coated surfaces, releasing particles smaller than 100 nm. Raman imaging revealed that individual scratches could release approximately 9,100 particles, while severely damaged coatings emitted up to 2.3 million particles [55]. The release of PTFE micro- and nanoplastics is exacerbated by repeated mechanical stress, abrasive cleaning, and elevated temperatures, all of which accelerate abrasion, embrittlement, micro-cracking, and coating detachment [49, 55, 92, 127, 129, 132]. In addition to cookware, PTFE-coated cutting boards have been shown to release particles ranging from 8 µm to 13 mm, leading to contamination of foods such as meat, with reported concentrations as high as 68.9 g^{-1} [143]. These findings confirm that PTFE fragments can leach into food during preparation and cooking [144]. The ingestion of PTFE-derived microplastics is an emerging health concern, particularly given the current limitations in analytical methods for detecting and characterizing nanoplastics [55].

While human exposure is likely widespread, the potential health effects, especially concerning male reproductive function, remain inadequately understood and require further investigation [145]. Actual microplastic release during typical cooking and cleaning is likely underestimated, as particles smaller than 10 µm are often excluded from quantification. Furthermore, abrasive cleaning contributes to environmental contamination via wastewater discharge [57]. For example, a recent study showed that during kitchen waste decomposition, microplastics between 4 and 400 µm were rapidly released, with up to 96.1% migrating into the liquid phase, 85.7% of which were found in the effluent, within just 20 h [139]. Environmental simulations have further demonstrated the vulnerability of PTFE to degradation. When exposed to UV light in seawater for six days, bulk PTFE released approximately 2.35×10^5 fluorine-containing microplastic particles per gram, with an average particle size of 2.7 µm and a mean mass of 28 picogram [146]. This degradation process is primarily driven by hydrolysis and acidification and is significantly influenced by temperature, emphasizing the need for more effective kitchen waste management practices to mitigate microplastic pollution at the source. Ultimately, PTFE-derived microplastics are released into the environment, where they may pose ecotoxicological risks that are currently underexplored and poorly understood (Fig. 4).

Environmental occurrence

Among 765 analyzed consumer products, eleven per- and polyfluoroalkyl substances (PFASs) were identified, with PTFE and perfluorodecalin being the most frequently detected, found in 25.9% and 22.2% of samples, respectively [147]. According to the European Commission, PTFE is commonly incorporated into personal care products, including lotions, sunscreens, and cosmetics, to enhance skin smoothness and visual appeal [148]. Beyond cosmetics, PTFE is widely used in non-stick cookware, medical devices, industrial machinery, and electrical insulation due to its unique properties, including chemical inertness and thermal resistance [57, 149]. Additionally, PTFE is prevalent in outdoor equipment such as waterproof clothing, tents, fleece garments, and climbing ropes, as well as in electronics

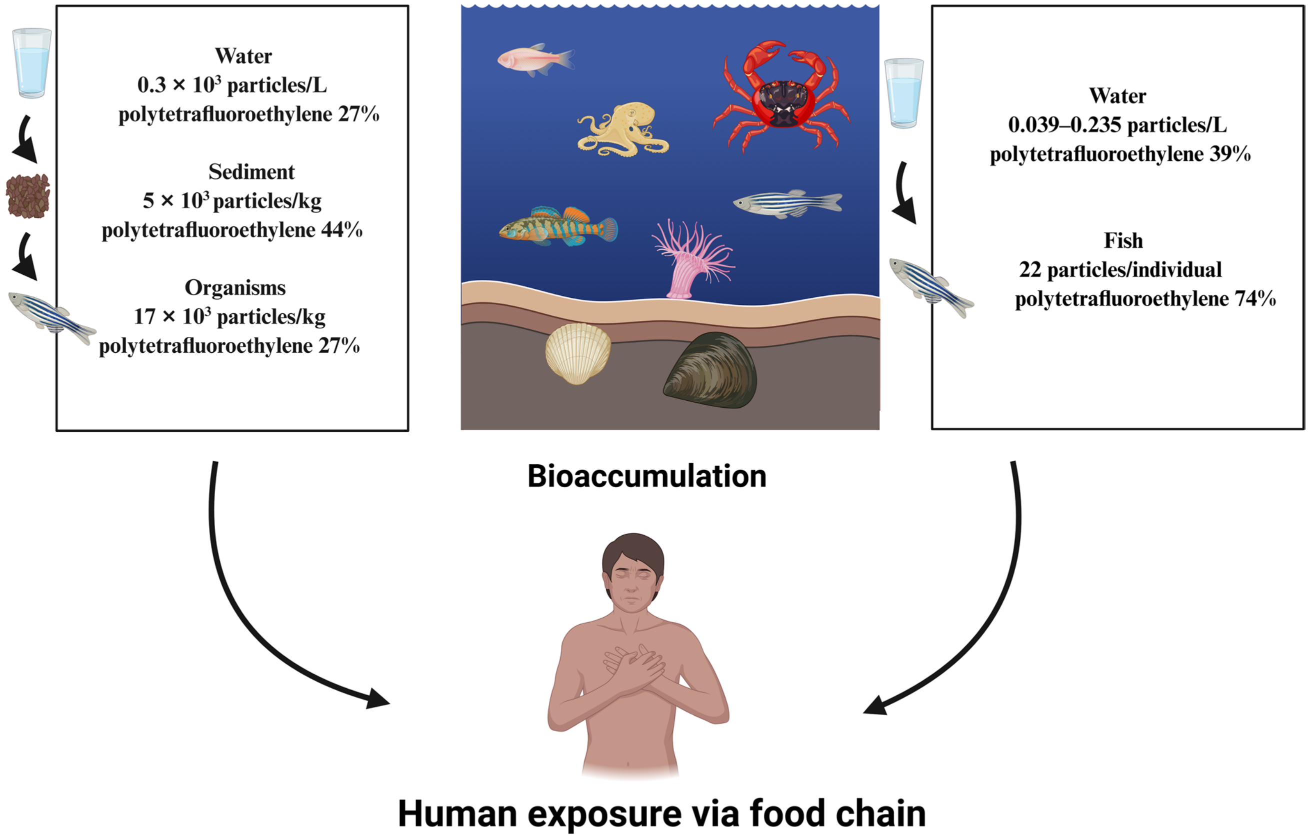

Fig. 4 Human exposure to polytetrafluoroethylene microplastics via the food chain. Polytetrafluoroethylene microplastics are widely distributed, often in high proportions compared to other microplastics, across environmental compartments such as water, sediments, and aquatic organisms. These particles can be transferred and bioaccumulated through the aquatic food web, progressing from water to sediments and into marine biota. Species frequently consumed by humans, including mussels, oysters, crabs, and fish, are particularly prone to polytetrafluoroethylene microplastic accumulation. Consequently, this may lead to human exposure through dietary intake and poses potential health risks. The percentage (%) denotes the proportion of PTFE microplastics relative to the total collected microplastics

and industrial components [150]. Environmental contamination by PTFE may occur through the fragmentation and weathering of products like cables and printed circuit boards [151]. The automotive sector is another major source, with PTFE being used in brake and fuel systems for its durability and heat resistance [152, 153]. Urban, industrial, and construction activities also contribute significantly to airborne PTFE microplastics, as the material is commonly employed in structural and electrical components [154].

Due to its widespread use and classification under resin identification code 7, PTFE lacks efficient recycling and degradation pathways, leading to its environmental accumulation, particularly in wastewater treatment systems, where its chemical inertness and persistence hinder removal [155]. Current management practices for fluoropolymers like PTFE typically involve landfilling, incineration, or limited recycling. However, these methods are largely ineffective due to the higher chemical stability of PTFE, which stems from its strong carbon–fluorine bonds [51, 156, 157]. This molecular inertness contributes to PTFE's persistence in topsoil and aquatic environments, with domestic sources such as the washing of PTFE-coated utensils likely exacerbating its environmental footprint [58]. Given its resilience and ubiquitous presence, there is an urgent need to develop targeted strategies for mitigating PTFE pollution and reducing its long-term environmental impacts [63]. The environmental distribution of PTFE microplastics across various matrices is further summarized in Tables 2 and 3. In addition, key findings from these tables are graphically represented in Fig. 5.

Atmosphere

Evidence of airborne PTFE microplastic contamination has been reported even in controlled laboratory settings, underscoring its pervasive environmental presence and raising concerns about unintentional human exposure [158]. Alongside acrylic and polyester fibers shed from waterproof clothing, PTFE contributes to the atmospheric transport of microplastics, an emerging area of study with currently limited data (Table 2) [159]. These microplastics are released

Table 2 Global distribution of polytetrafluoroethylene microplastics across different environmental matrices

Environmental matrices	Concentration	Size	Detection method	References
Water. Seventeen sampling sites, Wang Yu River network, Wuxi, China	2.3 ± 1.2–104.6 ± 5.6 particles/L (average, 52.2 particles/L) (PTFE, 30%)	lower than 330 µm	LDIR	[53]
Cooking cookware. PTFE-coated non-stick pans via simulated cooking experiment	9100 particles/scratch and damaged coatings releasing 2.3×10^6 particles	50–200 nm	SEM and Raman microscopy	[55]
Cookware. Plastic and PTFE-coated cookware, jelly as a food simulant	6.6 and 13.6 particles/meal and 2,409–4,964/yr	5–227 µm	FTIR	[57]
Soil. Agricultural soils with sludge or compost from wastewater. Southern Spain	$171.2 \pm 8.3 \times 10^3$ particles/kg (PTFE, 34.9% or 59.7×10^3 particles/kg)	100 to 500 µm (soils)	FTIR	[58]
Air. Atmospheric aerosol via a novel elutriation and oleo-extraction method, Italy	0.017 ± 0.003 particles/L (PTFE, 30%)	25.9 µm	FTIR	[153]
Water. Freshwater stream, Byers peninsula, protected area, Antarctic	$0.470–1.43 \times 10^{-6}$ particles/L (PTFE, detected)	1118 µm	FTIR	[159]
Indoor and outdoor (surgical environments), United Kingdom	1924 ± 3105 and 541 ± 969 particles/m^2/d in theater and anesthetic rooms, respectively (PTFE, 5%)	10–73 µm	FTIR	[160]
Atmosphere. Indoor and outdoor air, Taiwan	8.0 ± 10.7 (indoor) and 10.9 ± 14.1 (outdoor) particles/m^3 (PTFE, detected)	3–25 µm	Raman spectroscopy	[161]
Snow. Arctic surface snow, Svalbard Islands	141.2 µg/L	lower than 100 µm	FTIR	[163]
Sediments. Southwestern Atlantic coast, Argentine	19.78–1087.19 particles/kg (PTFE, lower than 2.22%)	lower than 500–23,450 µm	SEM/EDX, FTIR and XRD	[165]
Water. Thirty-one sampling sites, east China Sea to Arctic Region	$2.91 \pm 1.93 \times 10^{-3}$ particles/L (PTFE, 7.5%)	lower than 1000 µm	FTIR	[166]
Water: Anyang Stream tributary of Han River, South Korea	0.039 –0.235 particles/L (PTFE, 39.9%)	1000–5000 µm	FTIR	[167]
Sediment. Miri coast (26 sampling sites), Malaysia	170–700 particles/kg (PTFE, 36%)	1000–2000 µm	FTIR and Raman spectroscopy	[168]
Wastewater. Municipal wastewater treatment plants, South Korea	0.006–0.27 particles/L (PTFE, 46.5–56.5%)	lower than 300 µm	FTIR	[169]
Sediment. Lake Paldang in South Korea	$2.15–122.2 \times 10^3$ particles/kg (PTFE, 3.35% –31.5%)	45–100 µm	FTIR	[171]
Seawater and sediments. Da Nang's coastal areas, Vietnam	111–304 particles/L (PTFE, 6.8–26.5%) seawater and 2,267–4,600 particles/kg (PTFE, 16.7–44.4%) sediment	22.7–903.7 µm	FTIR	[172]
Soil. Soil samples of the cotton fields with continuous film mulching, Xinjiang Uygur, China	$1.98 \pm 0.41 \times 10^5$, $1.57 \pm 0.28 \times 10^5$, $1.78 \pm 0.27 \times 10^5$, and $3.20 \pm 0.41 \times 10^5$ particles/kg soil in cotton fields with film mulching of 5, 10, 20, and more than 30 yr, respectively (PTFE, 12.93 ± 6.09%)	500–5000 µm	LDIR and FTIR	[176]
Sediment. Archeological sediment samples, Wellington Row and Queen's Hotel, United Kingdom	$0–20.6 \times 10^3$ particles/kg (PTFE, 57%)	25–103 µm	FTIR	[177]
Water. Ikopa River, Madagascar	0.139 ± 0.009–0.222 ± 0.025 particles/L (PTFE, 28–55.9%)	lower than 300 µm	Raman microscopy	[180]

Table 2 (continued)

Environmental matrices	Concentration	Size	Detection method	References
Water. Aquaculture Technology Center of Andalusia (sea bass tank), El Puerto de Santa María, Cadiz, Spain	1.89–18.32 (9.54 ± 6.81) particles/L (PTFE, 7.41%)	63–100 µm	FTIR	[182]
Water. Ross Sea, Antarctic	$17 \pm 34 \times 10^{-5}$ particles/L (PTFE, 5.7%)	more than 60 µm	FTIR	[185]
Snow. Nineteen sites, Ross Island region, Antarctic	29 particles/L (PTFE, lower than 4%)	50–510 µm	FTIR	[186]
Sediment. Riverine sediment, Han River, South Korea	494 ± 280 particles/kg (PTFE, detected)	100–5000 µm	FTIR	[187]
Water. Kelantan and Langat rivers, Malaysia	179.6 and 1464.8 particles/L in Kelantan and Langat rivers, respectively (PTFE, detected)	500–5000 µm	FTIR, SEM–EDX and pyrolysis-GC/MS	[188]
Salts. Eight salt pans and 4 commercial salts. India	more than 50 particles/kg (PTFE, detected)	–	FTIR	[189]
Soil, five distinct agricultural regions, Bangladesh	130 ± 350 –3530 ± 1770 particles/kg (PTFE, 200 ± 660 particles/kg)	–	FTIR	[190]
Wastewater. 25 de Mayo (King George) Island, South Shetlands, Antarctica	64–159 particles/L (PTFE,7–8%)	20–200 µm	Raman spectroscopy	[191]
Sediment. Rhône River, France	$0.1\text{–}7.4 \times 10^4$ particles/kg (PTFE, lower than 6%)	lower than 5000 µm	FTIR	[192]
Wastewater. Water and sludge of five wastewater treatment plants, Changchun, Jilin Province, China	2530–18,240 (influent) and 650–1700 particles/L (effluent) (PTFE, 12–14%)	lower than 500 µm	LDIR	[193]
Soils. Tarim River Basin (TRB), China	570 particles/kg (PTFE, dominant)	100–1000 µm	FTIR	[194]

The concentration of polytetrafluoroethylene microplastic detected in various environmental matrices, primarily water and sediment from different countries worldwide. Polytetrafluoroethylene concentrations are reported either as standalone values or as part of a broader spectrum of microplastics, with or without specifying its percentage. Variations in measurement units are noted, primarily expressed as particles per kilogram or Liter. Polytetrafluoroethylene microplastics identify using Fourier transform infrared spectrometry (FTIR), Raman spectroscopy, laser direct infrared imaging system (LDIR) and scanning electron microscopy coupled with energy-dispersive X-ray spectroscopy (SEM–EDX) and reflection X-ray diffractometry XRD

Table 3 Global distribution of polytetrafluoroethylene microplastics in wild organisms across various locations

Environmental matrices	Concentration	Size	Detection method	References
Milk. Milk of Goat, cow, sheep, and buffalo milk	84.2 and 128 particles/L, with an average of 92.1 particles/L (PTFE, dominant)	20–150 µm	FTIR	[45]
Fish. One hundred and twenty mackerel (*Rastrelliger kanagurta*). Jakarta Bay, Indonesia	0.3 ± 0.3–4.8 ± 1.6 particles/gills and 0.4 ± 0.4–5.9 ± 2.3 particles/gastrointestinal tract (PTFE, dominant)	100 µm	FTIR	[144]
Honeybees, honey, and pollen samples. Campania Region, Southern Italy	Total collected particles 178 particles (PTFE, 7%)	190–3,525 µm (microfibers) and 68–779 µm (fragment)	FTIR	[162]
Fishes and water. Six species of inhabiting fish, namely carp (*C. carpio*), crucian carp (*C. cuvieri*), bluegill (*L. macrochirus*), bass (*M. salmoides*), catfish (*S. asotus*), and snakehead (*C. argus*). Han River, South Korea	0.039 –0.235 particles/L (PTFE, 39.9%) and 4–48 (22 ± 16) particles/individual, and in gills (1–16) with average (8.3 ± 6.0) particles/individual (PTFE, 74%)	300–600 µm	FTIR	[167]
Aquatic organisms (oysters, mussels, crabs, snails, fish), seawater and sediments. Da Nang's coastal areas, Vietnam	0.1–0.3 × 10^3 particles/L, 2.3–4.6 × 10^3 particles/kg, and 1.8–17.3 × 10^3 particles/kg in seawater, sediment and organisms, respectively. PTFE percentage; 6.8–26.5%, 16.7–44.4% and 2.6–26.9% in seawater, sediment and organisms, respectively	22.7–903.7 µm (sediment), 22.7–860.4 µm (water) and 29.7–563.7 µm (organisms)	FTIR	[172]
Aquatic organisms. Twelve macrobenthic species. Ross Sea, Antarctica	0.01–3.29 × 10^{-6} particles/kg or 1.0 particle/individual (PTFE, 14%)	50–100 µm	FTIR	[179]
Fish (gambusia and Nile tilapia) and water. Ikopa River, Madagascar	0.138 ± 0.009–0.222 ± 0.024 particles/L (water), 0.395 ± 0.317 × 10^6 (tilapia gastrointestinal tracts)– 2.275 ± 0.942 × 10^6 particles/kg (gambusia gills), (PTFE, 28–55.9%)	lower than 300 µm (water) 150 µm (fishes)	Raman microscopy	[180]
Fish. Twenty-eight species of deep-sea fish. Central Indian Ocean, off the Indian coast	4.96 ± 2.43 particles/individual (PTFE, 16.66%)	500 ± 4,690 µm	FTIR and Raman spectroscopy	[181]
Fishes. Twenty-two species. Han River, South Korea	15.6 ± 13.45–20.14 ± 10.01 particles/individual (PTFE, more than 16%)	100–200 µm	FTIR	[183]
Fish. Thirty-eight freshwater fishes (mostly *Zacco platypus*). Five sites along Han River, Gyeongan-cheon, South Korea	34–284 particles/individual (PTFE, 50%)	20–300 µm	FTIR	[184]
Fish (*Cyprinus carpio*). Vaal River, South Africa	26.23 ± 12.57 particles/individual or 41.18 ± 52.81 particles/kg (PTFE, dominant)	lower than 500 µm	Raman microscopy	[195]
Birds. Gastrointestinal tract of a semi-aquatic bird species, the cattle egret (*Bubulcus ibis*). Lahore, Pakistan	79.2 ± 22.7 particles /individual (PTFE, 8%)	–	FTIR	[196]

Polytetrafluoroethylene concentrations are reported as part of the broader microplastic profile, with or without quantification as a percentage of the total. To facilitate cross-study comparisons, all microplastic concentration measurements were standardized and expressed as follows: per Liter for water samples, per kilogram for sediments, and per kilogram or individual organism. The table also summarizes the analytical techniques used to identify plastic polymer fragments, including Fourier transform infrared spectroscopy (FTIR) and Raman spectroscopy

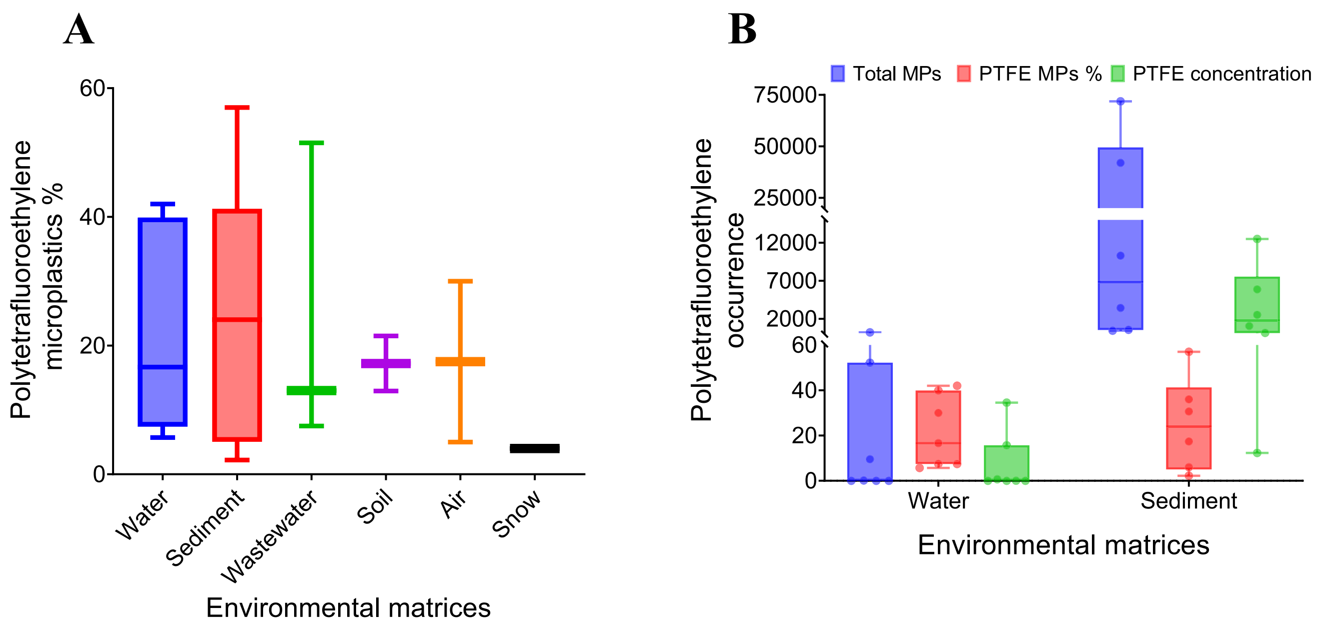

Fig. 5 **A** Percentage of polytetrafluoroethylene (PTFE) microplastics among total microplastics across environmental matrices. The dataset includes studies on water (n = 7), sediment (n = 6), wastewater (n = 3), soil (n = 2), air (n = 2), and snow (n = 1). Only studies that specifically quantify polytetrafluoroethylene microplastic proportions are considered. **B** Polytetrafluoroethylene microplastics relative to total microplastics in water and sediment. In water, the average concentration of total microplastics is 38.5 ± 76.9 particles/L (range: 0.00017–207.5), while polytetrafluoroethylene microplastics average 7.3 ± 13.3 particles/L (range: 0.00001–34.5), representing 21.5% of the total. In sediment, the average concentration of total microplastics is 21,428.7 ± 25,603.7 particles/kg (range: 435.0–71,850.0), with polytetrafluoroethylene microplastics at 3,685.7 ± 4,832.0 particles/kg (range: 12.3–12,501.9), accounting for 24.9% of the total

during the routine use of consumer products and can be dispersed across long distances under favorable meteorological conditions. Elevated concentrations have been observed in urban areas such as Mestre, Venice, reflecting the significant influence of anthropogenic activity [153]. In indoor environments, PTFE accounted for 5% of airborne microplastics detected in theater and anesthetic rooms [160]. Its widespread presence is further supported by studies that have identified PTFE microplastics in both indoor and outdoor air samples [161]. Notably, their detection in urban honey collected by bees supports their classification as persistent airborne contaminants [162]. Due to their small size (lower than 100 µm), PTFE particles are capable of long-range atmospheric transport, with documented occurrences in remote regions such as the Arctic [163]. However, PTFE remains underrepresented in atmospheric microplastic studies, likely due to limitations in conventional detection methods. The use of an improved five-step elutriation protocol revealed that PTFE can constitute up to 30% of airborne microplastics, averaging 17 particles per cubic meter of air [153]. These emissions were predominantly linked to industrial activities and vehicular sources, reflecting the widespread use of PTFE in automotive and structural applications due to its chemical and thermal resistance. Despite these findings, further research is critically needed to quantify ambient PTFE concentrations more accurately and to evaluate the potential health risks associated with prolonged inhalation exposure.

Sediments and water

PTFE microplastics have been detected in a range of aquatic and sedimentary environments, reflecting their widespread environmental dispersal. In the Arctic, PTFE particles (more than 500 µm) were identified in deep-sea sediment samples (2340–5570 m) from the Hausgarten observatory (see Table 2) [164]. PTFE microplastics (lower than 100 µm), capable of long-range atmospheric transport, have also been found in Arctic glacier summit waters, with concentrations reaching 141.2 µg/L. Nonetheless, their detection remains limited due to analytical constraints, and deposition mechanisms such as snow accumulation are still poorly understood [163]. Recent studies confirm presence in diverse geographic regions of PTFE. PTFE has been detected in coastal sediments along the southwestern Atlantic coast of Argentina [165]. Similarly, PTFE films were reported in a freshwater stream on Byers Peninsula, Antarctica, demonstrating contamination even in remote, ostensibly pristine environments [159].

In the Arctic Ocean, PTFE fragments and fibers accounted for 7.5% of all surface water microplastics, likely resulting from the degradation of high-performance materials such as printed circuit boards and cables [166]. Significant PTFE proportions have also been found in regional water bodies. PTFE made up 36% of sediment microplastics along the Miri coast in Malaysia and 39.9% in the Anyang Stream, a tributary of the Han River in South Korea [167, 168]. In municipal wastewater treatment plants in South Korea, PTFE microplastics constituted the dominant fraction (46.5–56.5%) despite the overall low abundance of microplastics (0.01–0.27 particles/L) [169]. These findings align with [58], who reported high PTFE concentrations in agricultural soils treated with sludge or compost from wastewater (34.9% or 59.7×10^3 particles/kg). However, some studies report no PTFE presence in surface waters, likely due to its high density (2.10–2.20 g/cm^3), which causes it to sink rather than remain suspended [156, 170].

According to Stokes' law, denser microplastics such as PTFE, polyester, and polyacryl settle faster than lower-density polymers like polyethylene and polypropylene, leading to accumulation of PTFE in sediments rather than in the water column [171]. Consequently, PTFE concentrations tend to be higher in sediments (16.7–44.4%) than in seawater (6.8–26.5%) and contribute to elevated ingestion rates among benthic organisms, such as crabs (76.9%), oysters (65.8%), and mussels (61.1%), compared to fish (57.1%) and snails (55.6%) [172]. Environmental factors, such as salinity, temperature, wind, and hydrodynamics, also influence PTFE distribution [167, 172–175].

PTFE, along with rubber and silicone, ranked among the most abundant of 22 polymer types identified in microplastic samples from urban river networks in eastern China, where seasonal and spatial distributions remained stable and industrial areas were the main sources [53]. PTFE microplastics have also been detected in agricultural soils with a history of plastic mulching and irrigation system use [176]. In archeological sediments from the historic city center of York, PTFE constituted 57% of the microplastic load (20.6×10^3 particles/kg), mainly in fragmented or irregular shapes [177]. Common morphologies include pellets, films, and fibers, with film microplastics being the most prevalent [176]. Notably, PTFE fragments and fibers were observed in 10 of 11 samples from the Arctic Central Basin, further supporting its pervasive presence [166]. The detection of PTFE-coated films in freshwater streams on Byers Peninsula also corroborates its environmental persistence across aquatic systems [159].

Wild organisms

Despite the limited number of biomonitoring studies specifically targeting PTFE, growing evidence indicates its widespread distribution in wildlife, particularly in fish, raising concerns about potential human exposure via the food chain (Table 3 and Fig. 4). Due to its high density (2.16 g/cm^3), PTFE tends to sink and accumulate in deeper layers of the water column, making it difficult to detect using surface-sampling tools like Manta nets. Consequently, PTFE contamination disproportionately affects benthic species, with bottom-feeding fish comprising 74% of contaminated individuals [167]. This high proportion suggests bioaccumulation, as PTFE levels in fish exceeded those measured in surrounding waters (39%). PTFE concentrations appear more strongly correlated with habitat than feeding behavior, as it was primarily detected in the intestines and gills of bottom-dwelling fish species, such as carp, catfish, and snakehead, which exhibited significantly higher PTFE loads compared to pelagic species [167, 178]. In Da Nang's coastal region, a consistent increase in microplastic concentrations was observed from water (111–304 particles/L) to sediment (2.3×10^3–4.6×10^3 particles/kg) to organisms (1.8×10^3–17.3×10^3 particles/kg), with PTFE constituting the dominant fraction in all compartments, demonstrating its transfer and accumulation within ecosystem [172]. Similarly, PTFE made up 14% of microplastics found in macrobenthic species from the Ross Sea, Antarctica [179].

In South Korea, PTFE concentrations in fish from five sites along the Han River and Gyeongan-cheon ranged from 17 to 142 particles per individual, with the highest detection rates in gills (55.9%) and gastrointestinal tracts (28%), while PTFE was absent from the water column samples [180]. In deep-sea fish from the Central Indian Ocean, PTFE was the second most prevalent polymer, representing 16.66% of all microplastics and averaging 2.68 ± 0.30 particles per individual [181]. In controlled environments, PTFE accounted for 7.41% of microplastics found in sea bass (*Dicentrarchus labrax*) tanks, with particles also detected in fish tissues [182]. PTFE microplastics (more than 16%, 0.1–0.2 mm) were reported in fish from the Han River, ranking third in abundance after polypropylene (more than 40%) and polyethylene (more than 23%) [183]. A follow-up study found microplastic concentrations in fish ranging from 34 to 284 particles per individual (20–300 µm), with PTFE levels peaking during the rainy season (up to 50%), suggesting meteorological influence on contamination patterns [184]. The higher microplastic concentrations in benthic organisms and consistency in particle types across water, sediment, and biota suggest bioaccumulation and raise concerns about food safety and ecosystem health [172].

PTFE has also been detected in terrestrial and airborne organisms. In honeybees, PTFE contamination was evident regardless of apiary location, supporting its classification as a ubiquitous airborne contaminant [162]. Additional studies detected PTFE in the hemolymph of *Blattella germanica* cockroaches, larvae and fecal pellets of *Lucilia* flies, the digestive systems of *Artemia salina* brine shrimp, and the cell walls of *Chlorococcus* algae [43]. PTFE was the second most abundant polymer in wastewater treatment plant effluents, reinforcing the importance of consistent environmental monitoring and improved analytical methods [53]. Most fish studies have focused on microplastics detectable by FTIR, which has a lower detection limit of ~ 10 µm, leaving a significant gap in our understanding of PTFE nanoplastics. Nevertheless, PTFE demonstrates clear bioaccumulation pathways, moving from water to sediments and eventually to aquatic organisms. In the Anyang Stream, despite low PTFE concentrations in water (0.039–0.235 particles/L), it represented up to 39.9% of all microplastics. Fish sampled from this stream averaged 22 microplastic particles per individual, with PTFE comprising 74% of that total [167]. Similarly, [172] recorded PTFE concentrations of $0.1–0.3 \times 10^3$ particles/L in water, $2.3–4.6 \times 10^3$ particles/kg in sediment, and $1.8–17.3 \times 10^3$ particles/kg in aquatic biota. In all compartments, PTFE accounted for more than 25% of detected microplastics. These findings confirm widespread environmental presence of PTFE, high potential for bioaccumulation, and associated ecotoxicological and human health risks (Fig. 4). In addition, key findings from Table 3 are graphically represented in Fig. 6.

Humans

The extensive use of PTFE-containing products has resulted in contamination of multiple human exposure pathways with PTFE-derived microplastics (Fig. 6 and Table 4). Key findings from Table 4 are graphically represented in Fig. 7.

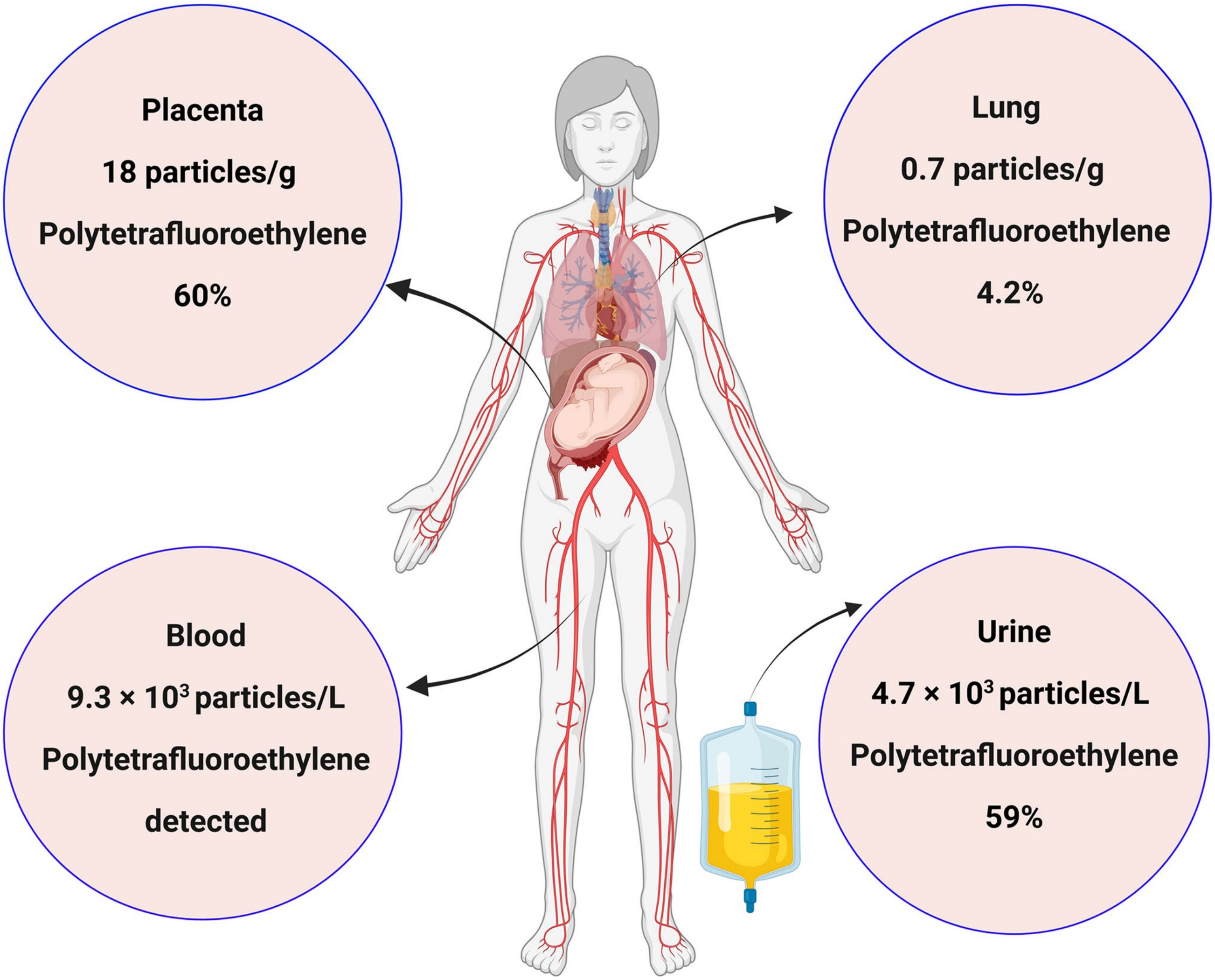

Fig. 6 Occurrence of microplastics in humans. Polytetrafluoroethylene microplastics have been detected in various human tissues, fluids, and excreta, alongside other microplastics derived from diverse plastic polymers. Remarkably, PTFE microplastics have been reported to account for up to 60% of total detected microplastics in certain cases, reflecting their extensive environmental prevalence. This widespread occurrence highlights the urgent need for comprehensive evaluation of their potential health effects and the development of appropriate risk mitigation strategies. The percentage (%) denotes the proportion of PTFE microplastics relative to the total collected microplastics

Table 4 Occurrence of polytetrafluoroethylene microplastics in human organs, bodily fluids, and urine

Human organ	Concentration	Size	Detection method	Reference
Lung (12 nonsmoking)	2.19×10^3 particles/kg (PTFE, 6.48%)	20–100 µm	LDIR and SEM	[59]
Placenta	0.62 particles/placenta (PTFE, 30%)	1.03–6.84 µm	Raman spectroscopy and Py-GC/MS	[60]
Urine (38 human urine samples)	$2.6 \pm 2.9 \times 10^3$ and $4.7 \pm 9.7 \times 10^3$ (PTFE, 59%) particles/L in healthy and endometriosis donors, respectively. No PTFE detected in urine of healthy human	10–128 µm (healthy) and 9–more than 300 µm (endometriosis)	FTIR and SEM–EDX	[61]
Lung	690 ± 840 particles/kg, PTFE (4, 19%)	4–88 µm	FTIR	[125]
Blood (23 patients after percutaneous coronary interventions)	$0.5 \pm 0.34 \times 10^3$ and $9.4 \pm 3.6 \times 10^3$ particles/L before and after percutaneous coronary interventions ($p < 0.001$), respectively (PTFE, detected)	29.33–213 µm	LDIR	[126]
Urine and semen (113 men, age of 32.72 ± 5.89)	26% and 40% of all microplastic of semen and urine, respectively	1.2–20 µm	Raman microscopy	[145]
Placenta and meconium	18×10^3 particles/kg (placenta) and 54.1×10^3 particles/kg (meconium) (PTFE, 0.68–4.06%)	20–50 µm	LDIR	[198]
Amniotic fluid (48 pregnant women)	39 samples contain, microplastics and PTFE found in 15 subjects (31.25%) the most prevalent polymer	3.05 ± 1.05 µm	Raman spectroscopy	[199]
Endometrial and urine samples from parturient women	24.2% and 51.7% of all microplastic of urine (the second dominant polymer) and endometrial tissue (the majority), respectively	1.23–6.98 µm	Raman spectroscopy and Py-GC/MS	[200]

Polytetrafluoroethylene concentrations are reported as part of a broader spectrum of microplastic, with or without specifying its percentage. To facilitate cross-study comparisons, microplastic concentration measurements mainly expressed per Liter for liquid samples and per kilogram for tissues. Additionally, the table includes the methodologies used to identify plastic polymer fragments, such as Fourier transform infrared spectrometry (FTIR), Raman spectroscopy, laser direct infrared imaging system (LDIR), scanning electron microscopy coupled with energy-dispersive X-ray spectroscopy (SEM–EDX) and pyrolysis–gas chromatography/mass spectrometry (Py-GC/MS)

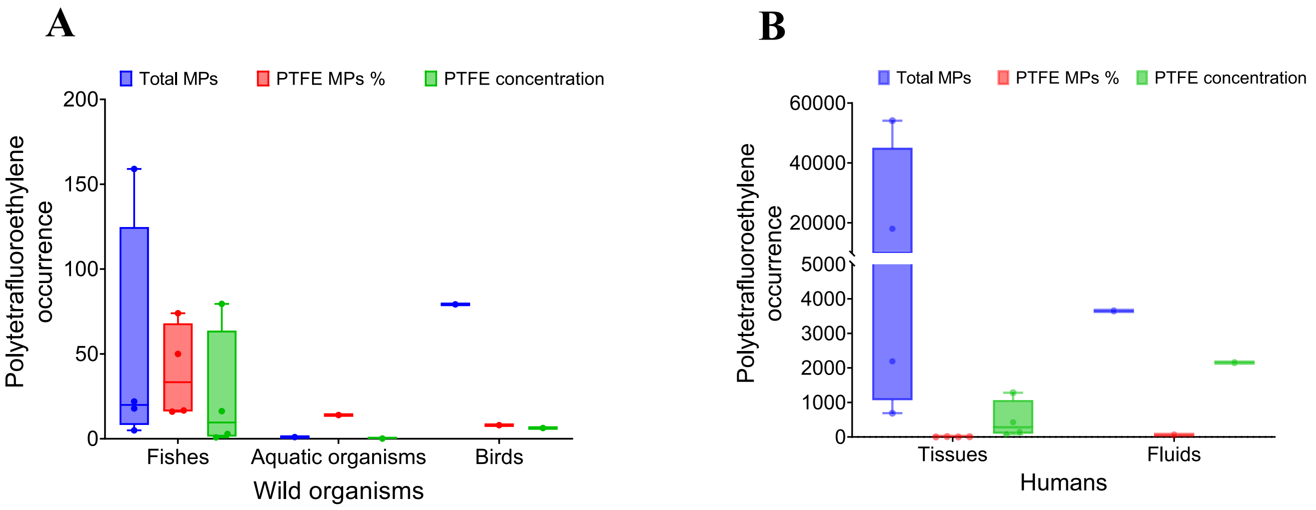

Fig. 7 **A** Occurrence of polytetrafluoroethylene (PTFE) microplastics in wild organisms. Data cover fish (four studies), aquatic invertebrates (one study), and birds (one study). Only studies reporting polytetrafluoroethylene microplastics quantitatively are included; qualitative studies are excluded. Concentrations are expressed as particles/individual for consistency. In fish, the average concentration of total microplastics is 51.0 ± 72.4 particles/individual (range: 5.0–159.0), while polytetrafluoroethylene microplastics average 24.9 ± 37.1 particles/individual (range: 0.8–79.5), accounting for 39.2% of the total. Other fauna groups contain only one reported value each. **B** Occurrence of polytetrafluoroethylene microplastics in human tissues and fluids. Data cover tissues (n = 4) and fluids (n = 1). Concentrations are expressed as particles/kg for tissues and particles/L for fluids. In tissues, the average concentration of total microplastics is 18,745.0 ± 24,836.7 particles/kg (range: 690.0–54,100.0), while polytetrafluoroethylene microplastics average 482.5 ± 554.1 particles/kg (range: 79.4–1282.2), representing 5.7% of the total. Fluids contain only one reported value

Potential sources of exposure include consumer products, occupational environments, and broader environmental contamination [60]. Everyday items such as cosmetics, textiles, and food-contact materials further contribute to this exposure [87, 147, 197]. PTFE was identified as the second most prevalent polymer in milk samples [45], and is commonly found in sediments, seawater, and aquatic organisms [172]. Additional exposure routes may include emissions from non-stick cookware or occupational activities involving PTFE, which can lead to an increase in overall human exposure [57]. These findings underscore the importance of quantifying PTFE microplastic concentrations in human tissues and bodily fluids.

Although comprehensive data on PTFE levels in human tissues, fluids, and excreta are limited, emerging studies indicate that PTFE is among the dominant microplastics detected in several human biological matrices. In lung tissue, PTFE accounted for up to 19% of all identified microplastics, with concentrations reaching approximately 142 particles per kilogram [59, 125]. In placental tissue, PTFE represented around 30% of the microplastic burden, with levels as high as 72 particles per kilogram. Strikingly, PTFE concentrations in meconium reached up to 2164 particles per kilogram, suggesting prenatal exposure and potential maternal transfer [60, 198]. Medical procedures are another potential source of PTFE microplastic exposure, particularly using polymer-based medical devices. It has been reported a substantial increase in blood microplastic concentrations following percutaneous coronary interventions, rising from $0.5 \pm 0.34 \times 10^3$ particles/L pre-intervention to $9.4 \pm 3.6 \times 10^3$ particles/L post-intervention, implicating medical equipment as a contamination source [126].

In urine samples from patients with endometriosis, PTFE constituted approximately 59% of detected microplastics (~ 3000 particles/L out of a total of $4.7 \pm 9.7 \times 10^3$ particles/L). In contrast, urine from healthy individuals showed significantly lower microplastic concentrations ($2.6 \pm 2.9 \times 10^3$ particles/L), with PTFE not detected [61]. These results suggest a potential link between PTFE exposure and certain health conditions. Similarly, PTFE was detected in semen samples, where it comprised 26% of all microplastics and was associated with sperm dysfunction indicators [145]. High PTFE levels (up to 40%) were also reported in urine samples, confirming its systemic distribution. Notably, PTFE was detected in amniotic fluid from 48 pregnant women, raising concerns over prenatal exposure [199]. Additionally, PTFE concentrations in endometrial tissue (51.7%) were markedly higher than in urine (24.2%), suggesting selective tissue accumulation likely influenced by the polymer's physicochemical properties [200]. The frequent detection of PTFE in human tissues and fluids raises significant health concerns, given its chemical stability, resistance to degradation, and potential for bioaccumulation. Although PTFE is known to cause granulomatosis upon thermal degradation, its toxicological impact at environmentally relevant concentrations remains poorly understood

[200, 201]. Environmental ubiquity and lifestyle-related factors likely contribute to the dominance of PTFE in human samples, warranting further investigation into specific exposure sources.

Current research on PTFE microplastic contamination in humans remains limited and at an early stage, highlighting the urgent need for more systematic investigations. Notably, no studies have yet reported the detection of nano-sized PTFE particles, largely due to the lack of suitable analytical methodologies. Existing data are further constrained by small sample sizes, limited scope, and inadequate sensitivity. Therefore, comprehensive biomonitoring using advanced techniques is essential to quantify PTFE micro- and nanoplastics in the human body. In parallel, toxicological studies are needed to assess potential health effects. Additionally, elucidating the transfer pathways of PTFE through the food chain is critical to gaining a complete picture of human exposure. Given its environmental persistence and extensive use, understanding the long-term risks of PTFE is vital for informing public health strategies, particularly in populations with higher exposure levels.

Toxicity

Since its introduction in the 1950s, PTFE has been widely used in non-stick coatings, automotive interiors, and personal care products, leading to an increase in human exposure, yet toxicological data on its particulate form in humans remain sparse [201, 202]. Notably, PTFE is exempt from registration under the European REACH regulation, limiting the availability of comprehensive safety data [157]. The International Agency for Research on Cancer (IARC) currently states that there is insufficient evidence to determine the carcinogenic risk of PTFE in humans, and no ecotoxicological effects have been definitively reported [62]. Despite its use in biomedicine and cosmetics, toxicity of PTFE remains underexplored [42, 197].

In humans, prolonged PTFE exposure has been associated with chronic health conditions. In occupational settings, workers exposed to PTFE particles during cookware coating processes developed granulomatous lung lesions after 7–20 years of inhalation exposure, likely due to the release of fine particles during high-temperature curing processes [201]. Analytical techniques, including scanning electron microscopy and infrared spectroscopy, confirmed the presence of PTFE in affected lung tissues. Similarly, in medical contexts, PTFE fibers used in surgical applications have been implicated in foreign-body inflammatory reactions, including "PTFE granuloma" [202]. PTFE exposure has been associated with immune suppression, thyroid dysfunction, liver damage, lipid dysregulation, and endocrine disruption, leading to increased regulatory scrutiny, particularly concerning its use in food packaging [203, 204].

Although PTFE is generally regarded as chemically inert and biocompatible, its ingestion and degradation raise concerns. At temperatures above 260 °C, PTFE releases polymer fumes; at 350 °C, exposure may cause polymer fume fever; and above 400 °C, hazardous pyrolysis products such as tetrafluoroethylene, perfluoroisobutylene, and fluorophosgene are generated [48, 205, 206]. These emissions can lead to respiratory symptoms, including chest pain, coughing, and in severe cases such as pulmonary edema [207, 208].

In vitro studies (Table 5) suggest significant biological effects of PTFE microplastics, although the number of scientific papers is low. In human cell lines, particles sized 6–32 µm induced oxidative stress, inflammation, and disrupted intracellular signaling pathways, with smaller particles exerting a stronger impact [209]. In murine intestinal organoids, PTFE exposure impaired mitochondrial function and suppressed the protein kinase B/mammalian target of rapamycin (AKT/mTOR) pathway, leading to reduced metabolic activity, necrosis, and autophagy [210]. A mouse oocyte maturation assay revealed reproductive toxicity at 10 µg/mL, evidenced by a significant reduction in oocyte maturation [211].

In vivo data (Table 6) present mixed findings. Some studies report no significant toxicity: rats exposed to dietary PTFE (5–50 µm; 0–2000 mg/kg) exhibited no adverse effects in clinical signs, organ pathology, or weight metrics [212]. Similarly, the marine gastropod *Littorina brevicula* showed no toxicological endpoints when exposed to PTFE [213]. Conversely, other studies report adverse outcomes: in mice, PTFE exposure altered immune responses, particularly in females, reducing the interferon gamma/interleukin-4 (IFNγ/IL-4) ratio and shifting toward a T helper type 2 (Th2)-dominant immune profile. Alterations in Immunoglobulin G subclass ratios further indicated immune dysregulation [214]. In duck embryos, PTFE exposure (5 mg/mL) caused 35% mortality, reduced vascular density, and neural developmental anomalies [215]. In *Drosophila melanogaster*, exposure disrupted energy metabolism and sleep, with males exhibiting reduced glucose levels and shortened sleep duration at 20 g/L, along with disrupted lipid and protein homeostasis [216]. Animal studies have reported tumor formation following PTFE implantation, although the relevance to environmental exposure remains uncertain [217–219]. Its monomer, tetrafluoroethylene is classified as a potential human carcinogen [220, 221]. Processing aids like perfluorooctanoic acid and hexafluoropropylene oxide dimer acid known as GenX, used in PTFE manufacturing, also present toxicological concerns. Though introduced as a safer alternative, GenX is persistent and has been shown to impair thyroid function and DNA integrity in rodent models [222–224]. These findings underscore the urgent need for further research into PTFE genotoxicity, which remains largely unexplored (see Fig. 8).

The toxicity of PTFE particles largely depends on size and exposure conditions, with smaller particles and prolonged exposure resulting in an increase in toxic effects. Ultrafine PTFE particles (~ 16 nm) generated at 486 °C caused acute lung injury in rats at concentrations as low as 50 µg/m^3 within 15 min, likely due to surface radicals or adsorbed toxic gases [133]. Pristine PTFE co-exposed with Cu^{2+} ions showed increased toxicity to *Microcystis aeruginosa*, impairing growth and photosynthesis, while aging increased metal adsorption, altering the particles' toxic profile [141].

Notably, among various microplastics detected in semen and urine, only PTFE showed a significant association with reduced semen quality [145]. This reproductive toxicity may stem from either PTFE particles or associated PFAS residues. PFAS concentrations above 10 µg/L in drinking water have been linked to polycystic ovary syndrome and potentially uterine leiomyoma and infertility, though not endometriosis [225]. Additionally, perfluorooctanoic acid (PFOA), commonly used in PTFE production, is a persistent endocrine disruptor with a multi-year half-life in humans [226, 227]. The fate of larger or ultrafine PTFE particles in the body remains unclear. Their insolubility and potential accumulation in organs such as the stomach or kidneys are areas of concern, but current literature lacks conclusive data [48, 228].

Analysis

Density-based separation of polytetrafluoroethylene microplastics

Microplastic separation is commonly achieved through density-based flotation, which involves suspending particles in high-density solutions so that those with lower densities float and can be recovered by filtration. The efficacy of this method hinges on the density contrast between the microplastics and the flotation medium. PTFE, with a high specific gravity (~ 2.2 g/cm^3), presents a notable challenge due to the limited availability of sufficiently dense and environmentally safe flotation solutions [169]. Although sodium chloride (NaCl) has a relatively low density (~ 1.2 g/cm^3), it has been employed in PTFE recovery. For instance, unexpectedly high PTFE recovery rates were reported in sediments (16.7–44.4% of total collected microplastics), compared to lower proportions in seawater (6.8–26.5%) [172]. However, other studies have demonstrated NaCl's inadequacy in isolating high-density polymers, often leading to their underestimation or complete omission [229, 230]. To overcome these limitations, denser flotation media such as zinc chloride

Table 5 Hazard impacts of polytetrafluoroethylene microplastics using various in vitro models

In vitro model	Size	Concentration	Impact	Reference
Six different human cell lines: Human colon adenocarcinoma cells (Caco-2), Human lung carcinoma cells (A549), Human myeloid leukemia promonocytic cell l (U937), Human monocytes (THP-1), Jurkat cells, and keratinocytes (HaCaT)	6.0 and 31.7 µm	10, 100, 500 and 1,000 µg/mL for 24 or 48 h	Activation of mitogen-activated protein kinase (MAPK signaling) pathways, particularly extracellular-signal-regulated kinase (ERK) through phosphorylation which plays a key role in apoptosis, cell morphology, proliferation, differentiation, and transformation. Induce oxidative stress, inflammation, and changes in cytokine production	[209]
Mouse intestinal organoids	–	50 µg/mL (7 d)	Reduced mitochondrial membrane potential, oxidative stress, and inhibited the protein kinase B/mammalian target of rapamycin (AKT/mTOR) signaling pathway. Disorder regulating fatty acid metabolism, nucleotide metabolism, necroptosis and autophagy pathways	[210]
Mouse oocyte maturation assay	100 nm	1 µg/mL, 10 µg/mL and 50 µg/mL	Exposure to 10 µg/mL significantly reduced oocyte maturation, as indicated by decreased metaphase II/germinal vesicle breakdown (79.81 ± 2.50% compared to 66.65 ± 5.02%, $p = 0.015$) and metaphase II /germinal vesicle (53.56 ± 3.30% *vs* 46.25 ± 0.73%, $p = 0.02$) ratios. No significant effects were observed at other PTFE concentrations	[211]

The table summarizes the experimental design of polytetrafluoroethylene microplastics including the size, period and exposure concentration. The endpoints of each experiment are outlined to provide a comprehensive understanding of the potential hazards associated with polytetrafluoroethylene microplastics

Table 6 Hazard impacts of polytetrafluoroethylene microplastics using various in vivo models

In vivo model	Size	Concentration	Impact	References
Rats	16 nm	50 µg/m^3, rates inhaled for only 15 min	PTFE fumes consisting of large numbers of ultrafine particles can cause severe acute lung injury	[133]
Algae (*Microcystis aeruginosa*)	2–20 µm	20 mg/LPTFE and 0.05 mg/L Cu^{2+} for 96 h	Inhibited microalgal photosynthesis and increased copper bioavailability. However, aging reduced their toxicity, both alone and when combined with Cu^{2+}	[141]
Rats	6.03 ± 2.10 µm and 31.65 ± 5.64 µm	500, 1000 and 2000 mg/kg via dietary intake for 4 weeks	No evidence of clinical effects (e.g., weight loss, morbidity, mortality)	[212]
Gastropod (*Littorina brevicula*)	0.1–10 µm	4 mg/cm^2	No toxic end points	[213]
Mice	6.0 or 30.5 µm	0, 500, 1000, or 2,000 mg/kg/d for 4-week exposure	Induced altered immune responses, with a dose-dependent shift toward Th2 dominance (decreased IFNγ/IL-4 ratio) in females. Changes in the IgG2a/IgG1 ratio in both sexes also suggested immune activation or dysregulation	[214]
Drosophila melanogaster	6.5 µm	0, 0.1, 1, 10, and 20 g/L for 20 d	Altered energy metabolism and sleep in *Drosophila melanogaster* in a sex- and dose-dependent manner. Males showed significantly reduced glucose levels and decreased sleep duration, particularly at 20 g/L. Disturbance in lipid and protein levels	[216]
Duck embryos	300 nm – 5 µm	0.01, 0.1, 1, and 5 mg/mL were administered starting on day 3 and continued to days 8 and 18	PTFE (5 mg/mL) microplastics caused 35% mortality and reduced vascular density in duck embryos, indicating anti-angiogenic effects. Treated embryos also exhibited brain and spinal abnormalities, including encephalomalacia and spinal cord discontinuities	[215]

The table summarizes the experimental design of polytetrafluoroethylene microplastics including the size, period and exposure concentration. The endpoints of each experiment are outlined to provide a comprehensive understanding of the potential hazards associated with polytetrafluoroethylene microplastics. IFNγ (Interferon gamma), IL-4 (Interleukin-4), Th2 (T helper type 2)

($ZnCl_2$, ~ 2.3 g/cm^3) have been adopted. PTFE microplastics were successfully recovered from stream water and fish tissue using $ZnCl_2$ [167, 183]. However, in other studies where $ZnCl_2$ solutions of slightly lower density (~ 1.7 g/cm^3) were applied, PTFE was not detected, likely due to instrumental limitations, particularly in Fourier transform infrared (FTIR) spectroscopy, rather than flotation inefficiency [231, 232].

Further advances include sequential flotation methods that enable separation across a broader density spectrum; Notably, a two-step protocol using sodium iodide (NaI, 1.6 g/cm^3) followed by zinc bromide ($ZnBr_2$, 2.3 g/cm^3) significantly improved the recovery of high-density particles such as PTFE microplastics from sediments [187]. Detection was particularly enhanced in fish samples collected during the rainy season, likely due to increased hydrodynamic resuspension of sediment-bound PTFE microplastics into the water column. These findings highlight the role of gravitational settling in the environmental distribution of dense microplastics like PTFE. Similarly, a five-step elutriation protocol revealed that PTFE particles were first detected from the third step onward, eventually accounting for up to 30% of all collected microplastics (17 ± 3 particles/m^3) by the final stage [153], emphasizing the necessity of multiphase separation approaches for accurately assessing high-density microplastic contamination.

Techniques for detecting polytetrafluoroethylene microplastics

PTFE is the second most abundant polymer found in wastewater treatment plant effluents, highlighting the importance of ongoing environmental monitoring using reliable detection methods [53]. PTFE microplastics serve as useful models in toxicological studies due to their distinct fluorine

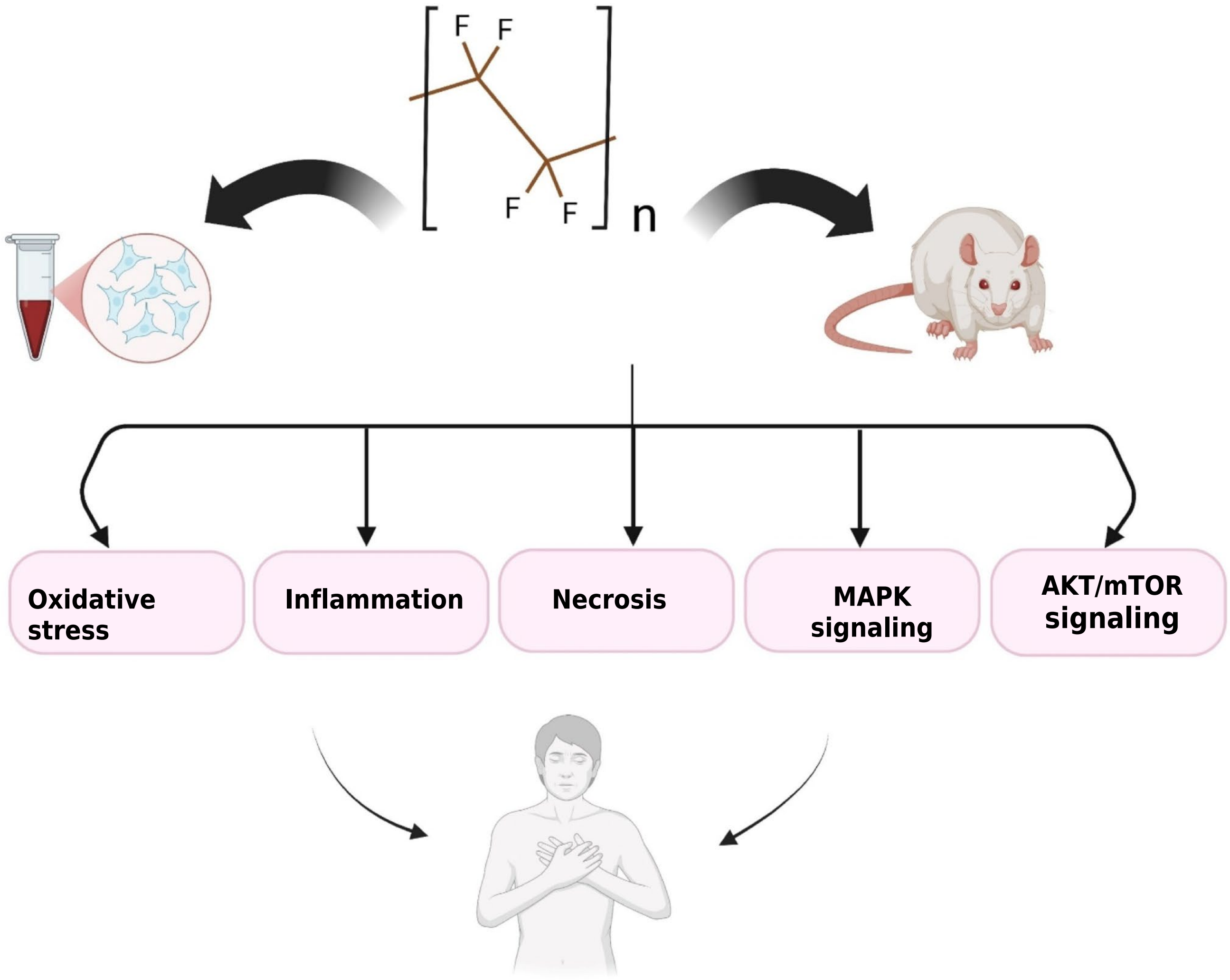

Fig. 8 Potential impacts of polytetrafluoroethylene microplastics. Studies using cellular and animal models have demonstrated that polytetrafluoroethylene microplastics can induce significant physiological disturbances by disrupting homeostasis and altering key regulatory pathways. polytetrafluoroethylene microplastics exposure has been associated with the induction of oxidative stress, inflammation, necrosis, and the activation of signaling pathways such as mitogen-activated protein kinase (MAPK) and protein kinase B/mammalian target of rapamycin (AKT/mTOR) pathways. These molecular responses highlight the potential adverse effects of polytetrafluoroethylene microplastics in the context of human exposure

content, crystalline structure, and physicochemical properties, which facilitate identification [43]. However, accurate detection remains technically challenging. Some proposed identification/quantification methods have been proposed as follows:

Fourier transform infrared spectroscopy (FTIR) is commonly used for microplastic identification, operating within a detection range of 4000–400 cm^{-1} and typically suited for particles larger than 10 µm [233, 234]. For example, in sediment samples from the Hausgarten observatory in the Arctic, PTFE was only detected in the more than 500 µm fraction, indicating the technique's limited sensitivity to smaller particles [164]. Laser direct infrared spectroscopy (LDIR) has improved PTFE detection, identifying it alongside polymers like silicone, rubber, and polypropylene [53]. However, its resolution still restricts analysis to particles more than 20 µm [126, 232].

Raman microscopy provides higher spatial resolution, enabling detection of particles as small as 100 nm and identification of plastic additives and pigments [235, 236]. Yet, weak Raman signal of PTFE and susceptibility to laser-induced degradation hinder its effective detection [237–239]. Consequently, up to 63% of microplastics can remain unidentified [64]. To address this, advanced techniques like two-dimensional correlation spectroscopy (2D-COS) and multi-spectroscopy methods combining FTIR and Raman have been developed [240, 241]. Image reconstruction using deconvolution algorithms further enhances signal-to-noise ratios and reduces analytical bias [33]. Complementary techniques also play key roles. Polarized light microscopy and energy-dispersive X-ray spectroscopy detect PTFE, via its birefringent properties and fluorine content [43], and X-ray diffraction has proven effective in characterizing structural changes in weathered PTFE [141].

Pyrolysis–gas chromatography/mass spectrometry (Py-GC/MS) thermally decomposes polymers into identifiable fragments, making it suitable for trace detection in biological matrices including blood, arteries, testicles, and semen [242]. While sensitive, Py-GC/MS is destructive and has limited efficacy for larger particles and for distinguishing polymer types [240, 243, 244]. Nonetheless, it complements spectroscopic techniques by offering chemical specificity. Integrated approaches enhance detection reliability. For example, combining Raman microscopy with Py-GC/MS allows both spatial and compositional analysis. In one study, this hybrid method detected PTFE in human placenta samples, where it represented 30% of total microplastics [60]. Similarly, in endometrial and urine samples from parturient women, Raman microscopy identified PTFE and polystyrene (PS) as dominant polymers, while Py-GC/MS further revealed polymers like polycarbonate, polyethylene, and polyvinyl chloride that Raman alone missed [200].

A novel advancement is fluorine-selective single-particle inductively coupled plasma tandem mass spectrometry (ICP-MS/MS). This method uses a barium-based plasma modifier to generate BaF^+ ions, allowing quantification of PTFE particles even in complex matrices like seawater [146]. Validation through microscopy and Raman confirmed its effectiveness in characterizing PTFE fragmentation and distribution. While FTIR and Raman remain essential tools, newer technologies such as LDIR, 2D-COS-enhanced Raman, and fluorine-specific ICP-MS/MS represent major strides in detecting PTFE microplastics across environmental and biological contexts. Currently, most detection techniques are limited to microscale particles, with nanoplastics (lower than 1 µm) largely escaping detection due to insufficient sensitivity and resolution [245]. As a result, the distribution, abundance, and potential health effects of nanoplastics remain poorly characterized [246–249]. Developing high-resolution, non-destructive techniques for nanoplastic detection is crucial for advancing our understanding of their environmental and biological impacts.

Policies

Although PTFE is widely regarded as chemically inert and valued for its industrial applications, emerging evidence points to significant regulatory gaps. Agencies such as the European Chemicals Agency (ECHA) and the United States Environmental Protection Agency (EPA) often overlook PTFE, underscoring the urgent need for specific policies addressing detection methods, exposure thresholds, and environmental monitoring. Broader efforts to manage microplastic pollution require coordinated international legislation, firmly grounded in scientific evidence. While instruments such as bans, levies, and voluntary agreements have shown some effectiveness, their fragmented application limits overall impact. Lifecycle-based policies—from material design through to disposal, combined with the establishment of a multilateral regulatory body, could support innovation, policy coherence, and more effective control of both general and PTFE-related plastic pollution [250].

Conclusion

Polytetrafluoroethylene (PTFE) is a widely used polymer valued for its exceptional chemical stability, thermal resistance, inertness, and non-stick properties. These characteristics have led to its broad application in industrial and household products, particularly in non-stick cookware. However, its extensive use has contributed to its pervasive presence in the environment, raising concerns about the ecological and human health implications of PTFE-derived microplastics. Recent studies have shown that everyday household activities, such as the use of PTFE-coated utensils, can release substantial quantities of micro- and nanoplastics. These particles are introduced directly into food and indirectly into the environment through wastewater generated during washing. As a result, PTFE microplastics are now frequently detected in water bodies, sediments, and aquatic organisms such as mussels, oysters, and fish (species often consumed by humans) indicating the potential for bioaccumulation and biomagnification. Their detection in human tissues, fluids, and excreta, sometimes constituting up to 60% of total microplastics, further highlights the significance of this exposure pathway. Toxicological investigations, including both in vitro and in vivo studies, indicate that PTFE microplastics may impair physiological homeostasis by inducing oxidative stress, inflammation, necrosis, and disruption of critical signaling pathways such as mitogen-activated protein kinase (MAPK) and protein kinase B/mammalian target of rapamycin (AKT/mTOR). Despite these findings, our understanding of the full scope of PTFE risks remains limited. A major barrier is the lack of standardized and sensitive analytical techniques capable of reliably identifying and quantifying PTFE microplastics, particularly at the nanoscale, in complex environmental and biological matrices. This technical gap hinders accurate exposure assessments and comprehensive risk evaluations.

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Declarations

Conflict of interest Authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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