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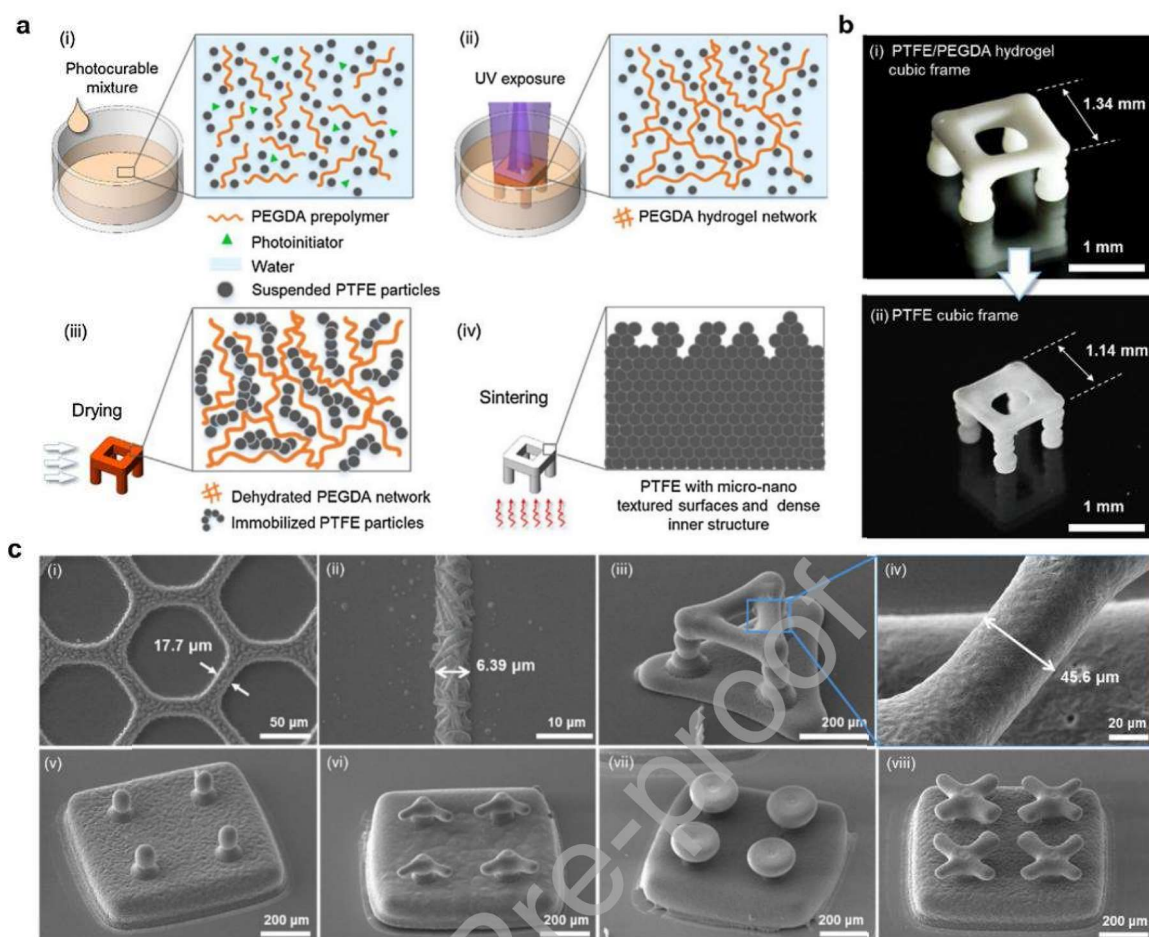


Fig. 58 : Schematic of the 3D μ -printing flowchart and images of the printed PTFE microstructures. (a) Printing flowchart: (i) Preparation of UV curable PTFE/PEGDA colloidal dispersion; (ii) Photocuring of the colloidal dispersion with a user-defined UV pattern; (iii) Drying of the printed microstructure to remove water; (iv) Sintering of the dried microstructure to remove PEGDA. Steps (i) & (ii) are repeated for 3D printing of microstructures. (b) Photographs of a printed cube-frame microstructure before and after sintering. (i) 3D printed and dried PTFE/PEGDA microstructure; (ii) 3D PTFE microstructure after sintering. (c) SEM images of 3D -printed PTFE microstructures: (i) micro-honeycomb structure; (ii) micro line; (iii) & (iv) 3D triangular-frame; (v) micro-ball array; (vi) zigzag micro-beam array; (vii) micro-mushroom array; (viii) suspended micro-cross array (reprinted with permission from ELSEVIER [249]).

More recently, Caldoni's group [251] supplied a comprehensive review on fluoropolymers in additive manufacturing. Furthermore, Phillips et al. [252] reported that PTFE, as a non-polar polymer filler, also plays a key role in reducing terahertz (THz) absorption when incorporated into photopolymer resins (Vero White®, supplied by the Stratasys company). PTFE-filled composites manufactured by stereolithography (or DLP) with filler ratios ranging from 1:10 to 4:10 exhibited progressively enhanced THz transparency as the PTFE content increased. The highest PTFE loading (approximately 30 wt.%) resulted in an absorption coefficient of $15.3 \pm 0.3 \text{ cm}^{-1}$ at 1 THz, which is a 27.8 % reduction compared to that of the pure photopolymer. This

enhancement can be attributed to PTFE's inherently low dielectric loss at THz frequencies (section 8).

The unique combination of chemical stability, thermal resistance, low friction, and electrical insulation continues to drive PTFE's broad adoption across industries, including aerospace, automotive, medical devices, electronics, construction, energy technologies, and advanced microfabrication, confirming its indispensable role in modern materials Science.

9.6. PTFE in automotive and transportation applications

In the automotive industry [226], PTFE is a key high-performance polymer of choice for components exposed to extreme operating conditions, thanks to its exceptional chemical resistance, thermal stability, and low-friction properties. Its primary applications include sealing and fluid-transfer systems, encompassing components such as gaskets, O-rings, valve stem seals, and linings for fuel and transmission hoses. In addition, with the rapid shift toward electric vehicles, micronized and compounded PTFE are being integrated into ultra-thin thermal and high-voltage wiring insulation. In these systems, the material's exceptional properties enhance vehicle reliability and ensure long-term durability.

Moreover, one of its most significant applications is in fuel lines, where it provides excellent resistance to gasoline, diesel, and other fuels and can withstand high pressures and operating temperatures, both of which are particularly important for high-performance engines. PTFE coatings are also commonly applied to automotive components, such as brake calipers, piston rings, and engine parts, to reduce friction and enhance durability. PTFE is also used in air-conditioning hoses, power-steering systems, and other high-pressure hydraulic lines thanks to its resistance to heat, moisture, and aggressive chemicals.

As demand for high-performance, long-lasting automotive systems continues to grow, PTFE's importance in fluid handling and sealing applications is expected to increase.

9.7. PTFE in medical applications

The medical sector benefits greatly from PTFE's biocompatibility and chemical inertness (for more information (section 10.)), as evidenced by its 38,400 metric tons usage in 2023, with over 17,000 hospitals adopting PTFE-coated surgical tools and medical devices to ensure non-stick surfaces and long-term durability. PTFE is used in implantable devices, such as coatings for stents, grafts, catheters, hernia mesh, and surgical mesh, as well as in prosthetics, leads, and foil for magnetic resonance imaging (MRI), computed tomography (CT), and mammography

machines [253,254]. The use of ePTFE extends to surgical instruments and equipment, including shears, cutters, and staplers used in minimally invasive procedures. Its presence is also notable in blood collection bags, suction devices used in respiratory therapy and anesthesia, and intravenous solution bags [255,256].

A comprehensive review of clinical trials conducted on ePTFE devices [255] underscores its extensive application: a total of 61 studies were identified in the field of guided bone regeneration for maxillofacial diseases, 43 of which focused on stents, hemodialysis, and bypass grafts. In addition, 8 studies concentrated on hernia repair, 8 on heart repair, and 14 on other medical fields [255]. These findings provide evidence that fluoropolymers such as PTFE are generally safe for use in body prostheses and medical devices (for more information, see section 10) [256,257].

9.8. Summary

PTFE's unique properties, including exceptional chemical inertness, high thermal stability, low coefficient of friction, and pronounced hydrophobicity, position it among the most advanced and reliable high-performance polymers available today. This makes it an essential component in applications where long-term stability, durability, reliability, security, and performance under extreme physical and chemical conditions are paramount.

10. Health Context: Is PTFE Hazardous?

10.1. PTFE is regarded as a Polymer of low concern (PLC)

According to the Organization for Economic Cooperation and Development (OECD) definition [258,259], PTFE is considered a PFAS. However, that definition does not say anything about molar mass or dispersity. Indeed, while PFOA and PFOS have molar masses of 414 and 500 $\text{g}\cdot\text{mol}^{-1}$, respectively, the molar mass of PTFE can reach several million $\text{g}\cdot\text{mol}^{-1}$ [1,9,11,15,16,260]. This large difference influences several features, such as water solubility, thermal and aging resistance, and the penetration (or not) of fluorochemicals into the lipidic human membrane [28,260,261]. As a consequence of its high molar mass, PTFE is highly insoluble (*e.g.*, in water, octanol, and solvents) [262] and thus is not mobile, solid, and too large to migrate into the cell membrane, making it non-bioavailable and non-bioaccumulative. More recently, Henry and Timmer [260] demonstrated that PTFE-FA (high molar mass, fine powder, microparticulate PTFE meeting the ASTM D4895 specification) does not i) exhibit any

mobility, ii) undergo degradation, iii) adsorb to soil or sediment, iv) partition from water or organic matter into air (as a gas or vapor), and v) undergo a long-range transport in air, water, or soil, nor transform into or release non-polymeric PFAS. Actually, it fulfills 13 of the PLC-accepted criteria set by the OECD [263], which cover parameters such as oligomer content, molar mass, dispersity, particle size, thermal, chemical, aging, and UV stability, as well as surface charge.

Therefore, PTFE can be considered a PLC from human and environmental health standpoints [260]. Although PTFE's applications have traditionally been evaluated primarily from the perspective of consumer use, Sales et al. [264] highlighted that its advantages are even more evident in industrial contexts, where it supports decarbonization, circularity, safety, reliability, durability and exceptional overall performance.

10.2. Biotic and abiotic

The Carbone-Fluorine bond is extremely strong (with a dissociation energy of $485 \text{ kJ}\cdot\text{mol}^{-1}$) and difficult to substitute. Thus, PTFE differs from hydrocarbon polymers related to their outstanding physico-chemical, thermal, and oxidative properties [1,4,7,10,11,265]. It exhibits a high degree of environmental stability due to such a strong carbon-fluorine bond. Under abiotic conditions [260] (Fig. 59), PTFE is considered chemically inert and resistant to hydrolysis, photolysis, and thermal degradation in conditions that are environmentally relevant, and it does not readily dissolve, disperse, or transform in aquatic or terrestrial environments. In terms of biotic factors [260] (Fig. 59), PTFE is also regarded as biologically inert, with no evidence of enzymatic degradation by microorganisms, plants, or animals. Its high molar mass prevents bioavailability, uptake, and bioaccumulation, and PTFE particles are expected to remain largely unchanged when passing through biological systems. Consequently, environmental exposure to PTFE is primarily associated with the physical presence of particulate material rather than chemical toxicity, an important consideration in environmental risk assessment [260,266].

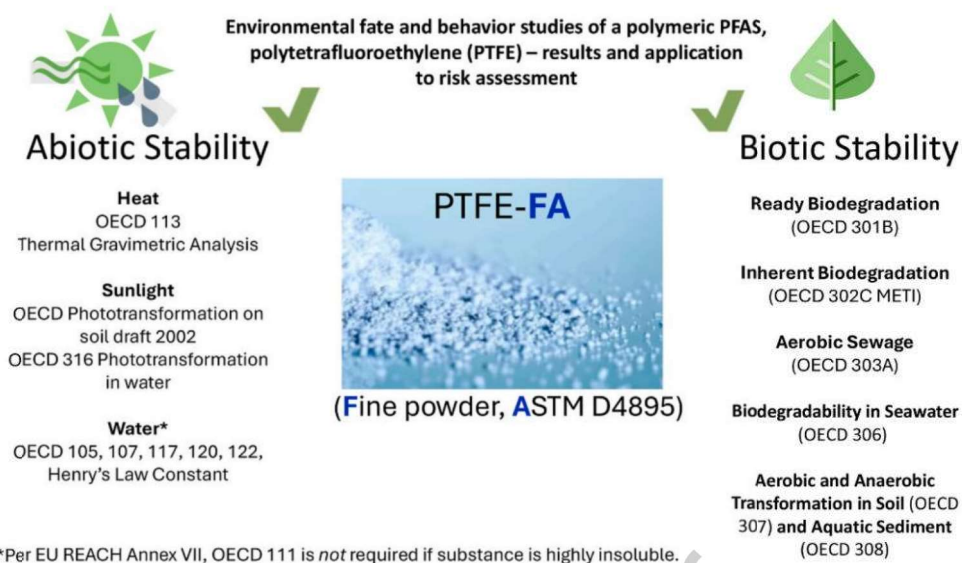


Fig. 59 : PTFE environmental fate: Persistence under abiotic and biotic conditions (reprinted with permission from ELSEVIER [260].

However, its persistence has pushed authorities and regulatory agencies to consider it as a PFAS, but useful [260]. Recently, Health Canada [267] has redefined the PFAS context in their PFAS regulations, excluding fluoropolymers for risk management purposes, despite the chemical structure. Since fluoropolymers have been excluded from this family grouping, they are also excluded from this determination regarding the Persistence and Bioaccumulation Regulations of the Canadian Environmental Protection Act, 1999 (CEPA) [267]. Though the PTFE production is the highest among all fluoropolymers, and it accounts for approximately 70 % of the overall fluoropolymer market [268] (some sources state that PTFE production is around 200,000 tons per year [229]), it is thus much lower than that of all plastics (< 0.1 %) [253,267].

10.3. Biocompatible

The essential-use concept [254] distinguishes between applications in which, based on current knowledge, no alternative materials can match the performance of PFASs [269], and those in which lower performance levels are acceptable and achievable. It also distinguishes between cases in which the use of PFASs is unnecessary. If it is desired to preserve access to the unique, unmatched performance of PFASs, the importance of making selective, environmentally responsible use of them is all the greater.

It quickly became clear that identifying situations in which the use of PFAS is unnecessary, and alternatives are available, is crucial. The OECD's revised definition [270] emphasizes that the term "PFAS" does not indicate whether a substance is harmful; it simply denotes compounds containing a fully fluorinated methyl or methylene group. Distinguishing between essential and

non-essential uses is therefore a key strategy for managing substances of concern effectively [254]. According to Decision IV/25.19 of the Montreal Protocol, a use is considered “essential” only if it is necessary for health, safety, or the functioning of society, and if no technically and economically feasible alternatives exist.

In 2023, the FDA approved a semi-fluorinated alkane, perfluorohexyloctane ($C_6F_{13}C_8H_{17}$, marketed as Miebo® trademark by Bausch and Lomb), as a preservative-free, single-component eye drop to reduce tear evaporation in the treatment of dry eye disease [271]. It is important to note that the active ingredients in pharmaceuticals, biocides, and plant protection products are regulated by frameworks other than REACH and are granted unlimited derogations in the EU PFAS restriction proposal. Given the potential risks associated with emissions, especially for plant protection products, the proposal recommends that the EU address these risks in the relevant regulations to minimize PFAS use and environmental release.

As a polymer, PTFE is not required to be registered under the European REACH regulation. The absence of regulatory incentives limits the amount of company-generated safety data disseminated to the public. To date, the most comprehensive safety assessment published concerns its use in cosmetics, conducted by the US Cosmetic Ingredient Review (CIR) expert panel [272]. According to this report, data from the Food and Drug Administration (FDA)’s Voluntary Cosmetic Registration Program (VCRP) indicates maximum usage concentrations of 13 % for products that remain on the skin, while 2.4 % for products that are rinsed off. It is worth mentioning that PTFE was used in cosmetics as a bulking agent thanks to its ability to reduce friction [272]. The substance has been incorporated into a variety of cosmetic products, including foundations, mascara, and lipsticks, to enhance texture and prolong shelf life (Table 9) [272]. Furthermore, to assess skin irritation and sensitization, two patch tests, one with 7.6% PTFE and the other with 12%, were performed on 26 and 15 human subjects, respectively. After 48 and 24 hours, respectively, no signs of irritation were observed in these people [272]. A repeated-insult patch test with 9% PTFE in 206 subjects also revealed no sensitization [272].

Table 9 : Frequency and Concentration of Use According to Duration and Type of Exposure of PTFE. (reprinted with permission from Sage [272]).

	PTFE	
	# of Uses	Concentration (%)
Totals/Conc. Range	365	0.11-13
Duration of Use		
Leave -On	343	0.11-13
Rinse off	22	0.15-2.4
Dilute for (bath) Use	NR	NR

Exposure Type		
Eye Area	229	0.11-13
Incedental Ingestion	4	NR
Incedental Ingestion-Spray	15 ^a	NR
Incedental Inhalation-Powders	31	0.6-3.0
Dermal Contact	325	0.11-12
Deodorant (underarm)	NR	NR
Hair- Non-Coloring	NR	NR
Hair-Coloring	NR	2.4
Nail	NR	NR
Mucous membrane	4	NR
Baby products	NR	NR

NR = Not Reported; Totals = Rinse-off + Leave-on + Diluted for Bath Product Uses. Note: Because each ingredient may be used in cosmetics with multiple exposure types, the sum of all exposure type uses may not equal the sum total uses. ^a It is possible that these products may be sprays, but it is not specified whether the reported uses are sprays.

Along with that, in an acute oral toxicity study conducted on rats, administering low-molar-mass PTFE resin did not result in mortality or clinical signs of toxicity at doses up to 17 g/kg [272]. In addition, a 90-day dietary study in rats with 25% PTFE reported no microscopic tissue changes. However, unsintered PTFE increased liver size [272]. In a nine-day inhalation study, exposure to a 20% PTFE dispersion produced no pathological findings, and mild respiratory symptoms were attributed to the propellants and dispersing agent rather than to the PTFE itself [272,273]. However, after six months of exposure to an unspecified concentration of PTFE, mice developed skin lesions, fur loss, and significant weight loss. Moreover, topical application of 20 % low-molar-mass PTFE resin in CCl₂F–CClF₂ (F-113) caused no skin sensitization in guinea pigs [273]. That review also reports that when 20 % low-molar-mass PTFE resin in F-113 was applied to rabbits' eyes, mild conjunctival irritation resolved within 72 hours and transient corneal injury resolved within 24 hours. Actually, these effects were comparable to those produced by the F-113 alone [273].

Furthermore, PTFE is recognized as non-carcinogenic and approved as safe and currently irreplaceable by authorities, including the FDA and the European Food Safety Authority (EFSA) [255,256].

Moreover, based on current knowledge, ca. 90 % of the fluoropolymers used in medical devices are PTFE [274], ETFE, FEP, and PVDF [256,275]. Expanded polytetrafluoroethylene (ePTFE) is also commonly used [256,255,276] (Fig. 60). Currently, there are no viable non-PFAS alternatives to these materials, and developing a substitute from conception to market is estimated to take 10 to 15 years. Moreover, banning PFAS would be risky, and it could

jeopardize millions of medical devices [256,277]. Indeed, upcoming PFAS regulations could significantly limit the availability of certain medical devices, which in turn may pose risks to patient safety. Physicians have begun issuing warnings about potential patient harm if the ECHA's proposed ban is adopted [277]. Several factors contribute to these concerns. PFAS such as PTFE are essential for coating guidewires, allowing them to move smoothly through blood vessels. Without PTFE and similar PFAS, guidewires may adhere to vascular walls, causing patient discomfort and increasing the risk of mechanical stress and thrombosis [256]. A range of medical procedures could be affected, including minimally invasive, endovascular, and gastrointestinal laparoscopic interventions. If the devices required for these procedures become less available, clinicians may have to rely more on open surgery, assuming that the tools needed for open procedures also remain accessible once a broad ban takes effect [277]. Furthermore, over 300,000 pacemakers and defibrillators are implanted annually in the United States, so a total PFAS ban could jeopardize access to these vital cardiac devices.

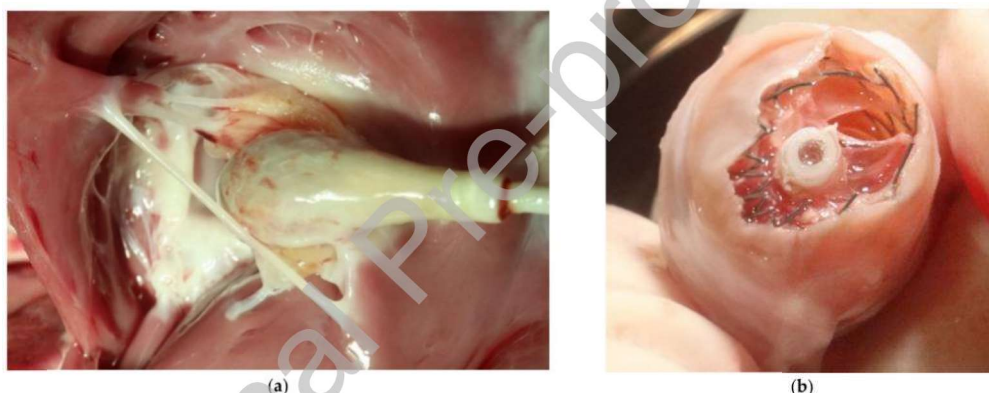


Fig. 60 : Gross estimation of the implanted spacer for Regurgitant Heart Valve Disease. **(a)** A smooth cell layer was formed over the ePTFE coating. The anterior leaflet, which has the most contact with the device, was slightly thicker than the other. **(b)** A seroma-like material was formed inside the self-expandable nitinol mesh (reprinted with permission from MDPI [276]).

In 2024, the American Cancer Society indicated that some PFASs are approved for use in the manufacture of non-stick cookware coatings. These coatings are made of PTFE and applied to the cookware through a heating process that tightly binds the polymer coating to the cookware, thus very little is capable of migrating into food, and no adverse health effects to be expected from cookware with PTFE non-stick coating according to the FDA [256]: "*The PFAS used in manufacturing of gaskets that come into contact with food do not pose a safety risk because they are also made of molecules that are polymerized*". As recently as January 2025, the FDA stated that the use of non-stick coatings is approved [256,278]. According to EU law, food-contact materials, including cookware, must be manufactured so that, under normal foreseeable conditions of use, they do not release chemicals into food in quantities that may be hazardous

to human health. Additionally, according to EFSA [279], several studies indicate that fluoropolymer food-contact materials are unlikely to be a significant source of PFASs.

In a similar context, the German Agency for Risk Assessment (BfR) conducted a thorough analysis of current PTFE-coated cookware, ovenware, and frying pans on the market. Under normal usage conditions (no overheating), these products do not transfer fluorinated chemicals into food in quantities that pose a threat to human health. This consensus scientific view is shared by environmental advocacy groups, such as the Environmental Working Group (EWG) [280]: In February 2024, this Group stressed that PTFE is not a significant source of exposure and reports: *“But even though it is always been the poster child for PFAS exposure, this cookware is not anticipated to be a major source of exposure”* [1,11,280].

Moreover, a series of studies was conducted by researchers at Golden Collar to evaluate the toxicity of PTFE-coated surfaces. These studies encompass a range of assessments, including animal tests [281] and evaluations of cellular toxicity. The potential toxicity of the substance is evaluated using animal experiments, which are designed to observe the physiological and pathological effects resulting from animal exposure to the substance. The evaluation of cellular response to PTFE exposure is conducted through in vitro cell cultivation, followed by meticulous observation of cell growth, proliferation, and apoptosis. This study indicates that PTFE does not elicit any toxic effects in humans under normal conditions. However, this does not imply disregard for the potential risks associated with using these devices. In certain instances, the coating may exhibit heightened toxicity, particularly if it is used to produce additives or solvents deemed unsafe.

Along the same lines and in terms of genotoxicity and teratogenicity, antiohesive coating materials containing 60-73 % PTFE tested negative in both the Ames test (mutagenicity test) and micronucleus assay [272], and a more recent comprehensive study confirms these features [260].

In conclusion, PTFE is a unique specialty polymer that meets the 13 OECD criteria for polymers of low concern thanks to its exceptional properties. The essential use concept helps to distinguish between applications with no non-fluorinated alternatives, those with effective substitutes and convenience uses that are therefore non-essential. This framework can inform the phase-out of non-essential uses of PFAS. Regarding the toxicity, the environmental risk depends on the quantities released.

Since the 1970s, public health authorities around the world have taken a unanimous position on PTFE: it is inert, non-bioaccumulative, non-toxic, not water soluble, and therefore safe for consumers.

However, assessing the essentiality of PFASs is challenging due to the large number of substances involved and the limited publicly available information on their structures, performance, production volumes, environmental behavior, and toxicity. Strengthened collaboration and information exchange among industry, academia, regulatory agencies, research institutions, and civil society are required to address this challenge.

From another viewpoint, PTFE, widely used for its stability and resistance, was once thought to be inert. In addition, data submitted to ECHA in 2023 [282], in public comments on the EU's proposed universal PFAS restriction, indicate that large PTFE fragments remain stable under environmental conditions, indicating a low likelihood of microplastic formation [260]. Besides, as mentioned in section 10.2. Biotic and abiotic, Health Canada has excluded fluoropolymers from the PFAS family [267], while the UK follows such a trend.

11. Fate of PTFE at end of life

11.1. PTFE waste, microplastics, footprint, and End-of-Life

Once manufactured and placed into service, the environmental impact of PTFE shifts from its production phase to its interaction with the surrounding environment.

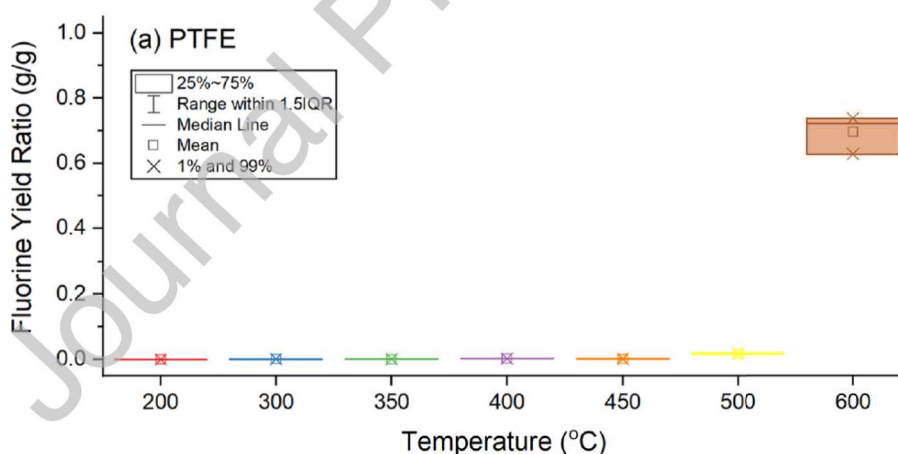
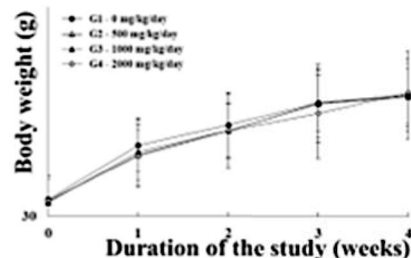


Fig. 61 : F yield (g/g_{fluoropolymer}) as a function of temperature for the thermal degradation of PTFE in air (reprinted with permission from ELSEVIER [283]).

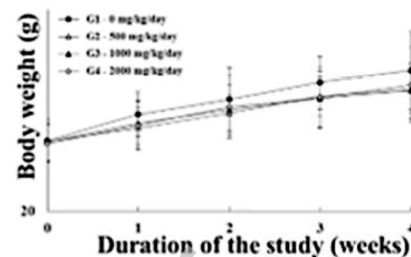
A significant benefit of PTFE is its remarkable resistance to chemical degradation, meaning it does not readily decompose or release harmful substances under typical operating conditions. This stability makes PTFE suitable for sensitive uses such as food processing (with specific grades) and medical devices (see section 10).

a approximately 5 μm , male

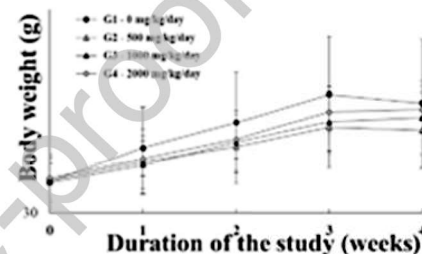
Dose \ Week	0	1	2	3	4
G1 - 0 mg/kg/day	31.2	35.1	36.5	38.1	38.7
G2 - 500 mg/kg/day	31.1	34.4	36.1	38.1	38.6
G3 - 1000 mg/kg/day	31.0	34.6	36.1	38.1	38.6
G4 - 2000 mg/kg/day	31.1	34.3	36.1	37.4	38.9

**b** approximately 5 μm , female

Dose \ Week	0	1	2	3	4
G1 - 0 mg/kg/day	25.3	27.2	28.3	29.6	30.5
G2 - 500 mg/kg/day	25.2	26.2	27.3	28.6	29.1
G3 - 1000 mg/kg/day	25.2	26.5	27.6	28.4	29.0
G4 - 2000 mg/kg/day	25.0	26.4	27.8	28.5	29.4

**c** 10–50 μm , male

Dose \ Week	0	1	2	3	4
G1 - 0 mg/kg/day	32.3	34.8	36.7	38.8	38.1
G2 - 500 mg/kg/day	32.4	33.8	34.9	36.4	36.1
G3 - 1000 mg/kg/day	32.3	33.6	35.2	36.7	37.1
G4 - 2000 mg/kg/day	32.6	34.0	35.4	37.5	37.7

**d** 10–50 μm , female

Dose \ Week	0	1	2	3	4
G1 - 0 mg/kg/day	25.4	26.5	28.5	30.5	29.7
G2 - 500 mg/kg/day	25.6	25.8	26.5	27.8	28.2
G3 - 1000 mg/kg/day	25.5	26.1	27.3	28.8	28.8
G4 - 2000 mg/kg/day	25.7	25.8	26.7	28.5	28.3

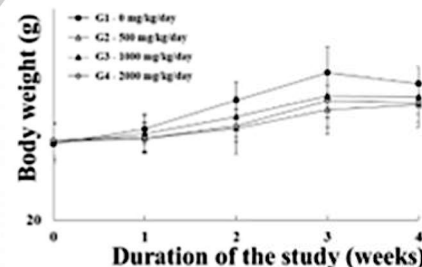


Fig. 62 : Male and female bodyweight changes after four weeks of repeated dosing with approximately 5 μm (a, b) and 10–50 μm (c, d) PTFE microplastics (reprinted with permission from MDPI [284]).

In addition, PTFE is generally biocompatible [256,260], does not support microbial growth, maintains reliable performance up to 260 $^{\circ}\text{C}$ in continuous service, and shows no significant degradation after 500 hours in laboratory aging tests [1,9,15,260]. Within this range, it remains stable without significant degradation or hazardous gas emissions [260]. According to other sources, PTFE remains essentially undegraded under moderate thermal conditions (≤ 500 $^{\circ}\text{C}$) (Fig. 61) [283]. Consequently, during its standard service life, PTFE is highly stable and poses a minimal direct environmental risk. While there is a small chance of microplastic formation [260], these microplastics do not lead to any hazardous issues [284–286].

Furthermore, given the low production of FPs (less than 0.1 % among all plastics) [253], the release of FP microplastics is quite low relatively insignificant compared to those from

commodity polymers [253,260]. The toxicity of PTFE microplastics (PTFE-MPs) has been investigated [260]. It indicates that PTFE-FA, even in microparticle form, neither increases PFAS levels in wastewater effluents nor inhibits microbial activity in sludge, in accordance with the ASTM D4895 specification [260]. Lee et al. [284] reported that after exposure to PTFE microplastics of 5-50 μm , no specific clinical sign was recorded during the 4-week observation period, and no significant differences were noted in body weight (Fig. 62), organ weight, or water and food consumption in the administration groups compared to the control group.

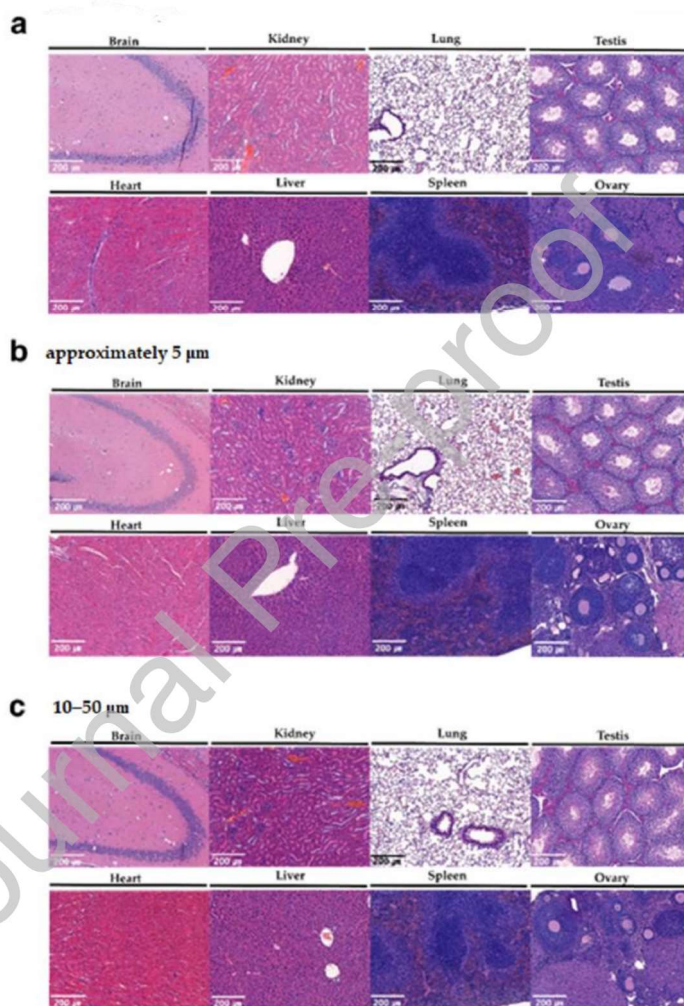


Fig. 63 : Histopathological evaluation of tissues from mice after four weeks of repeated dosing. Representative images of the brain (hippocampus), heart, kidney, liver, lung, spleen, testis, and ovary of the control mice (a), approximately 5 μm PTFE-treated mice (b), and 10–50 μm PTFE-treated mice (c). Scale bar = 200 μm (reprinted with permission from MDPI [284]).

Furthermore, no degenerative changes, such as inflammation, desquamation, or necrosis, were detected on histopathological evaluation (Fig. 63). Moreover, KC et al. [285] exposed six human cell lines representing tissues likely to come into contact with such particles to two sizes of irregularly shaped PTFE-MPs (6.0 and 31.7 μm). While no direct toxicity was observed, PTFE-MPs were found to affect different cell types. They appear to induce oxidative stress and

inflammation primarily through activation of the extracellular signal-regulated kinase (ERK) pathway, suggesting indirect, stress-mediated toxicity rather than direct cytotoxicity [285].

Alaraby et al.[286] also noted that the toxicity of PTFE particles depends on particle size and exposure conditions, with smaller particles and prolonged exposure increasing toxic effects. A comprehensive examination of the available literature on the subject reveals that toxicological investigations, incorporating both *in vitro* and *in vivo* studies, suggest that PTFE microplastics may potentially disrupt physiological homeostasis by inducing oxidative stress, inflammation, necrosis, and disruption of critical signaling pathways, including mitogen-activated protein kinase (MAPK) and protein kinase B/mammalian target of rapamycin (AKT/mTOR). Notwithstanding these findings, the comprehensive understanding of the full scope of PTFE risks remains limited [286]. A significant impediment is the lack of standardized, sensitive analytical techniques that reliably identify and quantify PTFE microplastics, particularly at the nanoscale, in complex environmental and biological matrices. This technical gap hinders accurate exposure assessments and comprehensive risk evaluations [286].

Overall, these findings demonstrate that the behavior of microplastics in the environment is not uniform and that their impact depends strongly on intrinsic properties such as molar mass, solubility, and bioavailability. This highlights the need for a more nuanced understanding to ensure that risk assessments and regulatory decisions accurately distinguish between particles that pose a high risk and those that have minimal environmental or biological relevance. Because of its unique characteristics, PTFE's high stability prevents its decomposition and raises questions about its release into microplastics.

As discussed above (sections 10.2 and 10.3), PTFE microplastics do not cause any problems. The primary concern is thermal decomposition at very high temperatures ($> 550\text{ }^{\circ}\text{C}$) [253,287]. Therefore, "secure landfilling" is recommended to prevent the material from fragmenting into smaller, more mobile particles in the environment.

In contrast to all plastics, FP consumption was estimated at 330,000 tons in 2021 [253] and 346,970 tons in 2023, although the exact figures vary by source. By 2028, the total market value of FPs in the Asia-Pacific region is expected to reach \$3.5 billion [253]. The relatively short life cycle of plastics also contributes to a sharp increase in the total amount of plastic waste. Currently, the global recycling rate for plastic waste is only 9% [253,288], while the recycling rate of fluoropolymers is merely 3.4% [253]. Similarly to all plastics [228,289], incineration is the main technique utilized for the elimination of FPs (it represented 83.5% in 2020, ca. 20.4 kt *versus* landfill, 13.1%, 3.1 kt and recycling, 3.4%, 0.8 kt), which is regarded as the destruction

of chemicals in the presence of heat and is mature technology used for various solid and liquid waste. Various reviews describe the incineration of PTFE [253].

It can be anticipated that, in the coming decades, many used polymers (including FPs) will accumulate, with their end-of-life management occurring via either incineration or landfill [253]. The incineration technique, generating hazardous hydrogen fluoride (HF) (and low molar mass PFAS), introduces potential risks to human health and the environment. In addition, landfilled plastic waste is exposed to a range of biochemical and enzymatic reactions and physical processes that may fragment it into microplastics [290,291], thereby raising health and environmental concerns [285,292,293]. The strong C–F bonds and stable helical conformation of PTFE (section 2) make it resistant to end-of-life degradation [16,294]. Recent studies have shown that PTFE microplastics can be detected and characterized using ICP-MS operated in single-particle mode [295,296]. This includes both SP-ICP-qMS approaches and F-selective SP-ICP-MS/MS techniques [295,296]. Thus, recycling processes, such as remanufacturing [253,297,298], degradation into valuable products, or, better yet, mineralization for possible circularity, would be of great interest.

Current technologies for disposing of discarded PTFE can be roughly divided into three categories: physical separation, chemical oxidation, and thermochemical conversion. Among them, thermochemical conversion technologies, i.e., pyrolysis, gasification, and combustion, outperform the former strategies by thoroughly destroying and mineralizing the large amounts of organic fluorine, providing an efficient, scalable, and widely available way to dispose of PTFE without producing PFAS-containing waste [299,300].

11.2. Recycling (chemical, thermal, mechanical, and using gamma irradiation)

Recycling PTFE has intensified and is challenging [253,268], although it exerts much pressure and poses potential hazards to the ecological environment. Various methods for recycling PTFE have been reported: gamma, electron beam, and proton radiation [57,303–307] have shown side products [308] but thermal depolymerization has been studied in most studies.

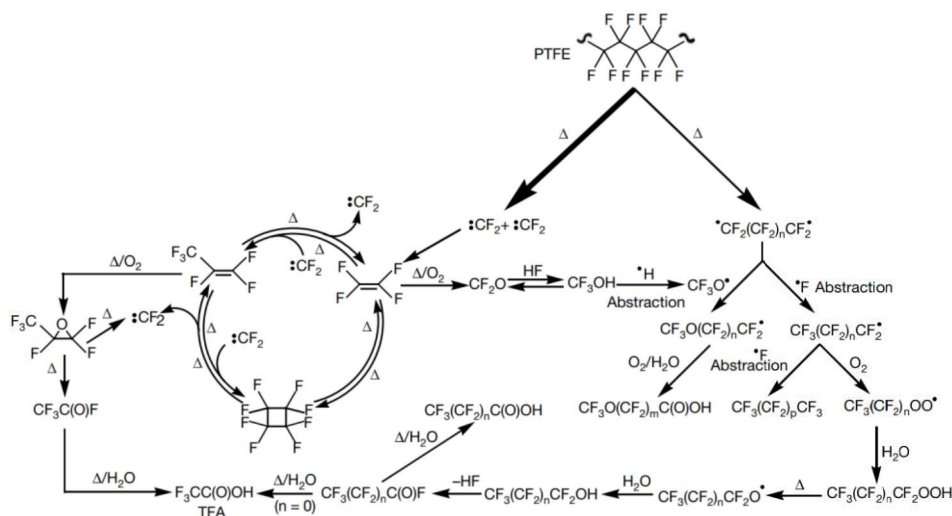


Fig. 64 : Proposed significant pathways in the thermal decomposition of PTFE, highlighting unexpected fluorochemicals. (reprinted with permission from Nature [309]).

The thermal “unzipping” or depolymerization of PTFE (from 550 °C), releasing TFE and other fluorochemicals, has been known since the 50s [287,309–313] and has also been industrialized in a pilot plant [313]. These unexpectedly generated chemicals and TFE were identified by various analytic tools (especially liquid chromatography mass spectroscopy, LC-MS...) [309,314,315] (Fig. 64 and Fig. 65).

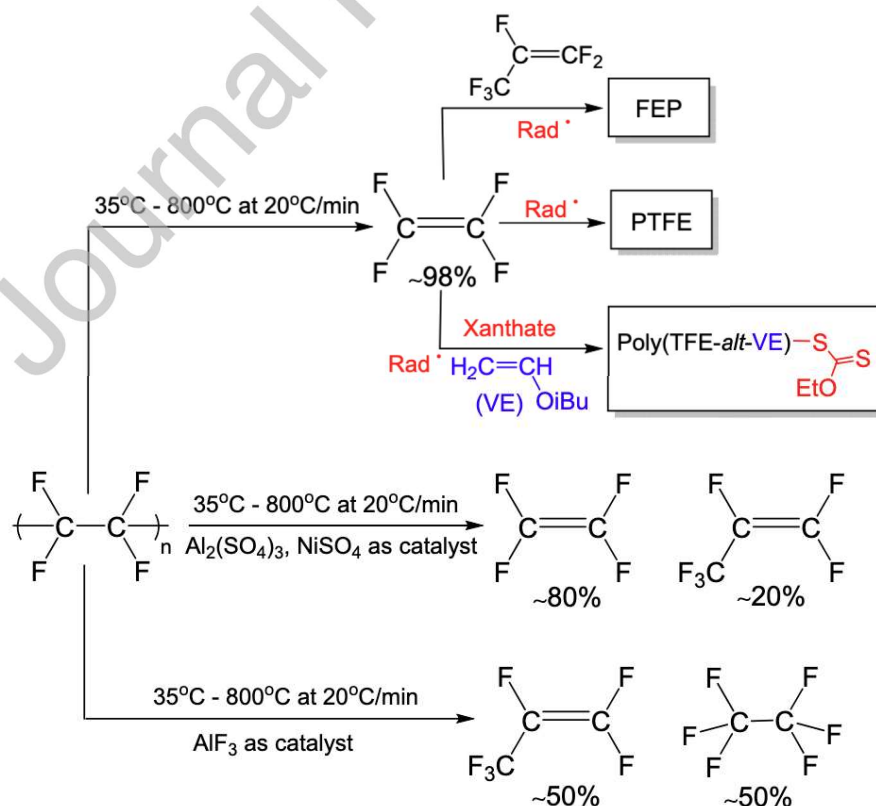


Fig. 65 : Thermal recycling of TFE from the thermolysis of PTFE with or without a catalyst and use for further (co)polymerization (readapted from MDPI [11,97,98,316]).

More recently, Yu et al. [268] reported a critical review on the current and global situation of PTFE (and its waste resources) recycling technologies, involving mechanical recycling and radiation cracking of PTFE, as well as recovering monomers from PTFE pyrolysis (though several references were missing) with anticipated development of environmentally sustainable and economically feasible chemical upgrading strategies [97,98,268], thus accelerating the process of industrializing the use of PTFE waste. A quite recent study by Lowe et al. [317] described a mechanochemical strategy for the reductive defluorination of PTFE, yielding an environmentally benign mixture of elemental carbon and sodium fluoride. The process employs inexpensive, commercially available chunks of sodium metal (though flammable; not specified) and proceeds rapidly at room temperature without any organic solvent. Remarkably, sodium fluoride (NaF) is obtained in 98 % yield (Fig. 66). Furthermore, the fluoride generated in the process can be directly upcycled *via in situ* mechanochemical fluorination reactions, delivering valuable sulfonyl fluoride and acyl fluoride products in excellent yields (Fig. 66).

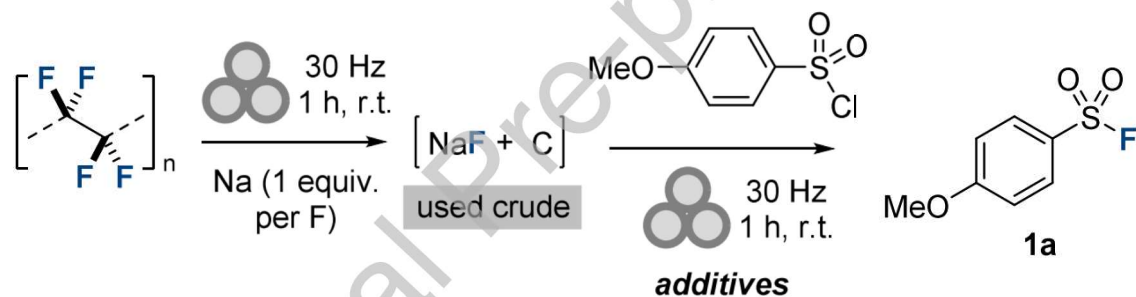


Fig. 66 : Mechanochemical Upcycling of Fluorine from PTFE to Sulfonyl Fluorides (reprinted with permission from ACS [317]).

Xiang and Tao [318] designed PTFE composites incorporating recycled PTFE waste powders, which were first compacted by compression molding at 40 MPa at room temperature in a cuboidal die and subsequently sintered at 380 °C for 2 h. Their results show that reprocessing PTFE debris can preserve mechanical integrity and enhance tribological properties, further illustrating the potential for a circular approach to PTFE. Moreover, Xi et al. [319] presented a mechanical recycling process for discarded PTFE/glass fiber laminates, in which the waste material is pulverized and recombined with new PTFE and glass layers to produce remanufactured composites that retain dielectric and structural properties comparable to those of the original material.

Chemical recycling of waste PTFE represents an advanced strategy [253,319] that transforms discarded plastics into high-value chemicals and fuels through processes such as thermal catalysis and other techniques [320].

Having demonstrated the recyclability of PTFE, the following section focuses on its degradation and mineralization.

11.3. Degradation-Mineralization

11.3.1. Thermal degradation of PTFE

Aleksandrov et al. [321] degraded TFE-based FPs waste (containing a mixture of FPs, Table 10) by means of a *BRENNkammer mit Dampfkessel* (Brenda) pilot plant. This enabled the authors to convert the mixture into inorganic fluorides, CO₂, and HF. Indeed, that efficient process requires high temperatures (850-1000 °C) to lead to no residual PFAS (< 1 ng/m³) in only 2 seconds. The same German team [322] revisited the incineration of FPs at their end of life and provided data supporting the mineralization of FP waste. They noted negligible PFAS release as products of incomplete combustion. These authors burned a mixed sample of FPs, representing 80% of commercially available FPs, under conditions representative of municipal and industrial waste incinerators operating in Europe. They used state-of-the-art emission sampling and Ultra-high Performance Liquid Chromatography coupled with tandem Mass Spectrometry (UPLC-MS/MS) and GC-MS to identify and quantify the released PFAS, for which standards were available and useful for this relevant work. Statistical analysis of the results confirmed the absence or insignificant amounts of PFAS, highlighting such efficient FP mineralization.

Chu et al. [323] investigated the microscopic thermal decomposition pathways of PTFE by combining plasma gasification experiments with multi-scale simulations. Molecular dynamics simulations identified two distinct degradation pathways: a pyrolysis-oxidation and chain-shortening-deep defluorination (POCD) route in oxygen, and a fluorine abstraction-hydrolysis-deep defluorination (FHD) route in steam. Density functional theory (DFT) calculations revealed the key roles of ¹O₂ and ·H radicals in breaking the PTFE carbon backbone, supporting the proposed mechanisms. Experimental validation confirmed the simulation results, demonstrating that up to 80% of gaseous fluorine can be recovered within 5 minutes during plasma gasification, with optimal conditions determined *via* response surface methodology [323].

Table 10 : Mixture of various FPs in treatment of Brenda (where PFA and FKM stand for poly(TFE-*co*-perfluoroalkyl vinyl ether) and poly(VDF-*co*-HFP) copolymers or poly(VDF-*ter*-HFP-*ter*-TFE) terpolymer, respectively) [321].

Materials	Weight Fraction (wt.%)
PTFE tubes	63
PTFE tapes	7
PVDF	18
PFA	6
FKM Rubber	6

These researchers have begun to question the effectiveness of thermochemical conversion methods for PTFE mineralization, as well as the potential hazards posed by fluorinated byproducts. This creates an urgent need for more efficient, advanced PTFE mineralization technologies. To this end, a thorough examination of the intermediate and final products, thermal decomposition mechanisms, and effects of operating conditions during PTFE treatment is crucial. In addition, plasma-based techniques [117] have gained interest as a promising approach for FP degradation.

It is worth noting that Boucher et al. [324] and Koch [325] observed that the addition of nonvolatile basic compounds, such as calcium hydroxide $\text{Ca}(\text{OH})_2$ and sodium hydroxide, can suppress the release of gaseous products (*e.g.*, atomic fluorine ($\text{F}_{(\text{g})}$)) during the thermal treatment of PTFE.

11.3.2. Mineralization via catalysts

A Japanese team [326] used molten alkaline metal hydroxide (NaOH, more efficient than KOH) to mineralize PTFE. The authors found that a simple, easy, and environmentally benign strategy based on a two-step procedure promotes the chemical recycling of PTFE to achieve effective mineralization. As a matter of fact, that route seems a bit surprising, since it is well known that

liquid sodium can react with PTFE. In the first step, PTFE was decomposed to soluble alkaline fluorides by degradation in molten hydroxides at elevated temperatures (500 °C). In a second step, CaF_2 , an essential starting mineral for all Organofluorine Chemistry, was obtained by treating the previous aqueous solution with CaCl_2 . PTFE was thus mineralized and, when heated with a large excess of NaOH at 500 °C for 3 h, 74 % yield of CaF_2 was obtained (Fig. 67). Actually, these temperatures are close to those enabling the unzipping depolymerization of PTFE [309].

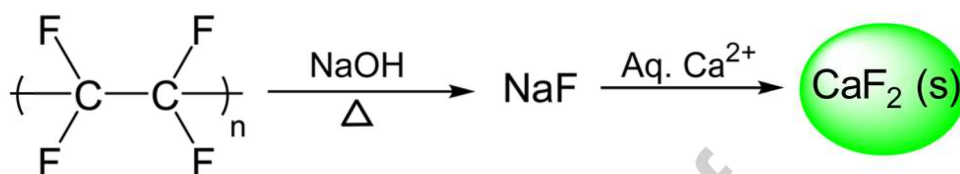


Fig. 67 : Suggested process of mineralization of PTFE by molten NaOH (reprinted with permission from RSC [326]).

These Japanese authors reported that (i) no decomposition was noted in the presence of molten NaOH below 400 °C, while ii) at 600 °C, the CaF_2 yields dropped to 46 % (from 67 % and 74 % at 450 °C and 500 °C, respectively, Fig. 68) [326].

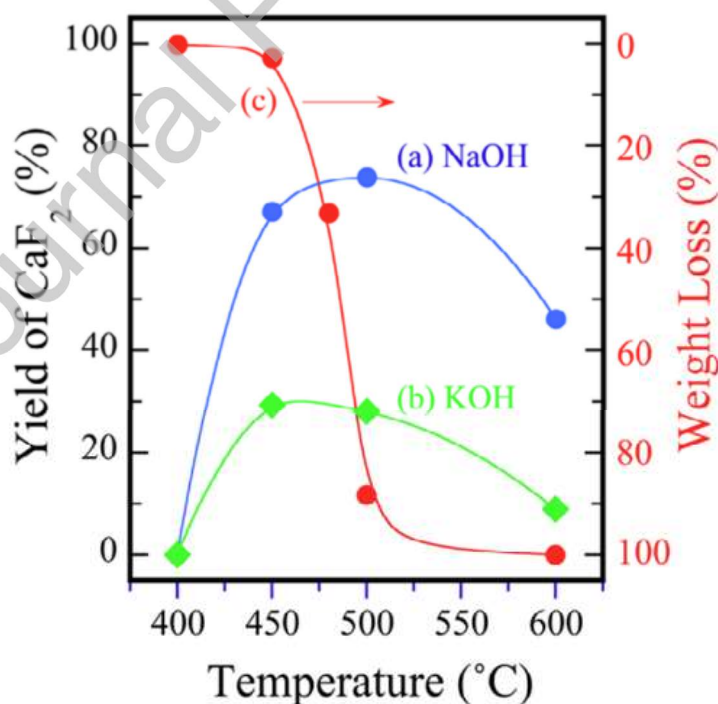


Fig. 68: Temperature dependence of PTFE degradation by molten alkaline hydroxides (curves a and b) and simple isothermal weight loss of PTFE (curve c). In each attempt, ca. 5 mmol of PTFE and an excess of MOH (M = Na, K) were used (reaction for 3 h at various temperatures under air) (reprinted with permission from RSC [326]).

For an increase of temperature up to ca. 450 °C, the macromolecular chains exhibit vigorous molecular motion, and chain scission occurs in the PTFE backbone. Subsequently, various small segments are generated from an unzipping mechanism [312]. The resulting fragments of the main chain underwent further scission to yield oligomers and/or low molar mass-derivatives. The obtained small molecules (*i.e.*, oligomers and monomers) then react with O²⁻, which attacks the carbon atom according to a nucleophilic pathway to generate CO₂ and eliminate F⁻.

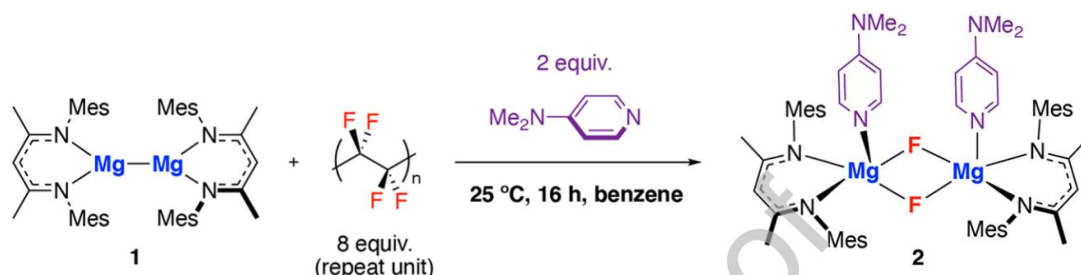


Fig. 69 : Room temperature reaction of magnesium complex **1** onto PTFE oligomers (reprinted with permission from ACS [327]).

Another approach involves a nucleophilic magnesium complex **1** (Fig. 69) that could react onto PTFE oligomers at room temperature, releasing a molecular magnesium fluoride, which was easily separated from the surface-modified PTFE [327]. The fluoride, in turn, could be utilized to transfer the fluorine atoms into a small array of compounds. This proof-of-concept study shows that the atomic fluorine content of PTFE can be harvested and reused in chemical synthesis.

11.3.3. Degradation by mechanochemistry

Mechanochemistry is a versatile room-temperature technique that supports green chemistry by enabling efficient, solvent-free or solvent-minimized reactions [328,329]. In this context, in addition to the above study on the valorization of PTFE [317], two recent mechanochemical investigations on the mineralization of PTFE have been reported. First, in 2025, the Gouverneur's team [330] proposed the total degradation of PTFE in the presence of phosphate activators at room temperature (Fig. 70), thereby returning to KF, which can serve as the fluorine source for further fluorination chemistry. At the same time, Shibata's group [331] used KOtBu or other bases at 100 °C but reached a lower yield (42 %) on PTFE.

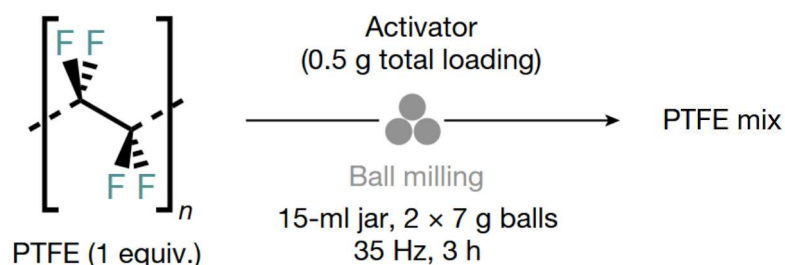


Fig. 70 : PTFE degradation induced by phosphate activators at room temperature (reprinted with permission from Spring Nature [330].

More recently, the British group [332] also used the same strategy to decompose PTFE in presence of silicate while Chen et al. [333] and Ackerman et al. [334] used metal nitride and KOtBu as activators, respectively in yields better than those reported by Shibata et al. [331]. Overall, Fig. 71 represents an interesting timeline, summarized by Lowe et al. [335].

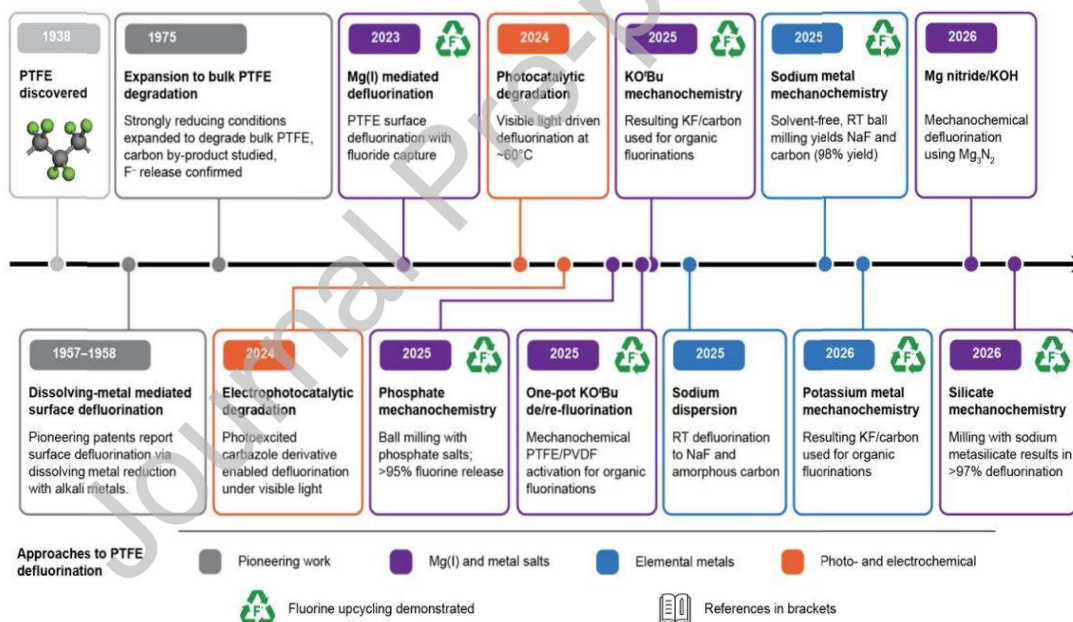


Fig. 71: Timeline, chronology and milestones for low temperature PTFE degradation and fluorine upcycling (reprinted with permission from the RSC [335].

11.3.4. Other methods of degradation of PTFE (chemical, tribochemical, and degradation by irradiation)

Park's research group [336] reported a chemical degradation approach for the e-PTFE support used in Proton Exchange Membrane Fuel Cell (PEMFCs), involving its reaction with radicals

and hydrogen peroxide during a Fenton reaction. After the Fenton reaction, the main chain of e-PTFE is cleaved, leading to significant changes in the support's chemical structure and morphology, thereby decreasing its tensile strength. However, the authors did not report a complete degradation of the e-PTFE [336]. Another simple and efficient method for the degradation of PTFE was reported by Nag et al. [337] in the presence of conventional metals such as gold, copper, zinc, silver, and iron (stainless steel) in an aqueous solution of carbohydrates like glucose and cyclodextrins, leading to the degradation of the polymer [337]. Nevertheless, the high cost of certain metals limits the industrial feasibility of this method. Fluoropolymers can also decompose when exposed to irradiation [117,268,303,338–341]. Dams and Hintzer [342] reported the degradation of high M_n fluoropolymers by electron beam radiation as a commercial process. However, this procedure leads to the formation of PFOA as a by-product at concentrations greater than 25 ppb. Nevertheless, the combination of irradiation and heat treatment in an oxygen-free atmosphere can reduce the formation of PFOA to less than 5 ppb [308].

11.4. Environmental Impact and Life-Cycle Assessment (LCA)

The recent study from Henry and Timmer [260] depicts a comprehensive analysis that PTFE does not induce any environmental issues due to its high thermal, aging and chemical resistance. LCA data on PTFE remain limited, yet available studies indicate a relatively high environmental footprint, particularly during production. The global warming potential (GWP) of CF_2ClH , the raw materials used for TFE synthesis, including upstream natural gas, chlorine for chloroform, fluorite (or Fluorspar), and sulfuric acid for hydrogen fluoride production, is estimated at 10.65 kg CO_2 -equivalent per kg TFE, based on cradle-to-gate data. For a PTFE-lined piping (2 in. diameter, 5 mm wall thickness), the carbon footprint was calculated to be 29.5 kg CO_2 -eq per meter of pipe, compared to 41.3 kg CO_2 -eq/meter for equivalent stainless-steel piping under similar operating conditions. Other industrial sources report that the production of 1 kg of PTFE generates between 7.06–7.8 kg of CO_2 [260] or ca. 13–18 kg of CO_2 [229]. Actually, when PTFE is used in wind turbine bearings, it can extend the turbine's operational life by up to 15 years. The reduced maintenance and replacement needs of these initial emissions are effectively "offset" within two to three years of operation. From another perspective, PTFE's environmental impacts are minimal during its use phase due to its durability, chemical inertness, and long service life [260].

12. Limits, challenges, prospects and outlooks

12.1. Irreplaceable polymer and possible alternatives to PTFE

As discussed in this review, PTFE has been used for many decades in a wide range of industrial and consumer applications due to its special and unique properties. However, following the European Union's restrictions on PFAS, which include PTFE, it has become essential to identify suitable substitutes. Actually, so far, no substitute of PTFE has been found.

To address this lack of PTFE alternatives, two recent AI-based studies have been reported. The first one examined more than 33,000 documents, including reviews, publications, patents, and scientific reports, to propose two interesting possible alternatives which failed when tested under conditions as aggressive as those tolerated by PTFE.

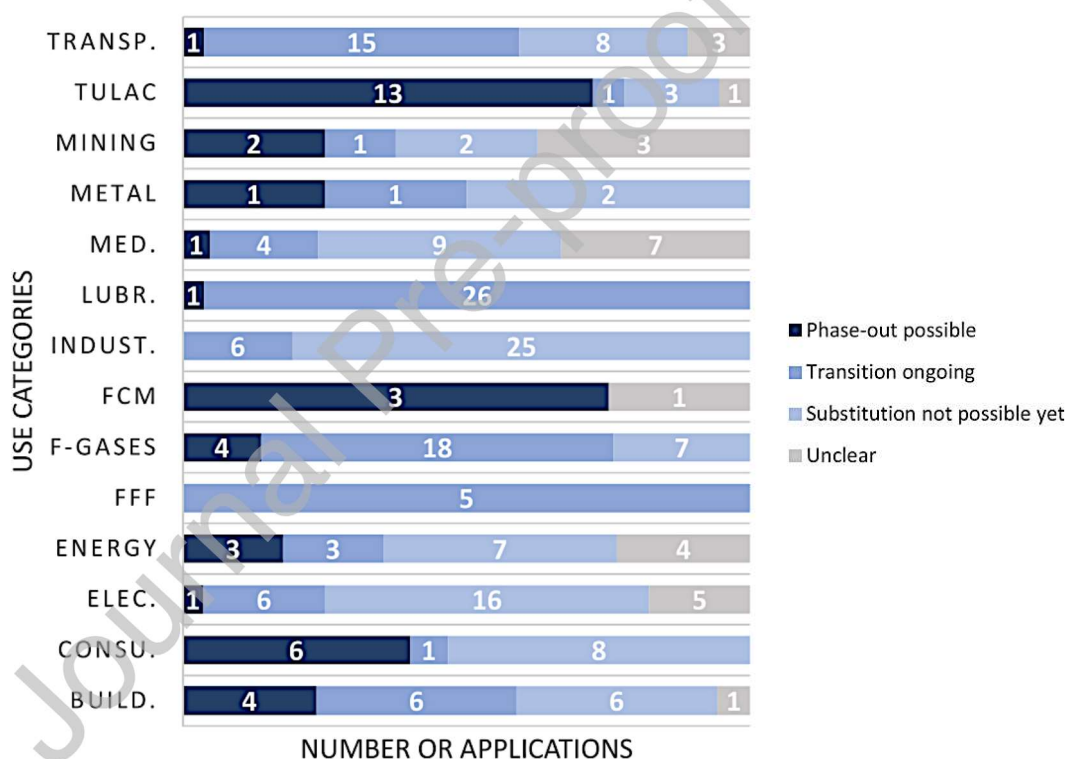


Fig. 72 : Substitution Potential of PFAS (reprinted with permission from ACS [343]).

The other study also identified various sectors and noted a total of 530 PFAS-free alternatives [343]. Based on a screening of potential concerns for the identified alternatives, their performance relative to PFAS, and their market availability, it is concluded that potentially suitable alternatives to PFAS are available for 40 applications. For 83 applications, no alternatives could be identified at the time of the study, and “*should be the focus of further research activities*”. Fig. 72 displays the potential for substituting PFAS in each use category. At last, for 93 applications, either no suitable alternatives have been identified at the time of the

analysis, or the suggested alternatives are still under development and not yet available on the market.

Moreover, from the Office of the Assistant Secretary of Defense for Energy, Installations, and Environment, no alternative has yet been identified to replace PTFE membranes, and it is estimated that from conception to market, a viable PFAS alternative would take 10 to 15 years.

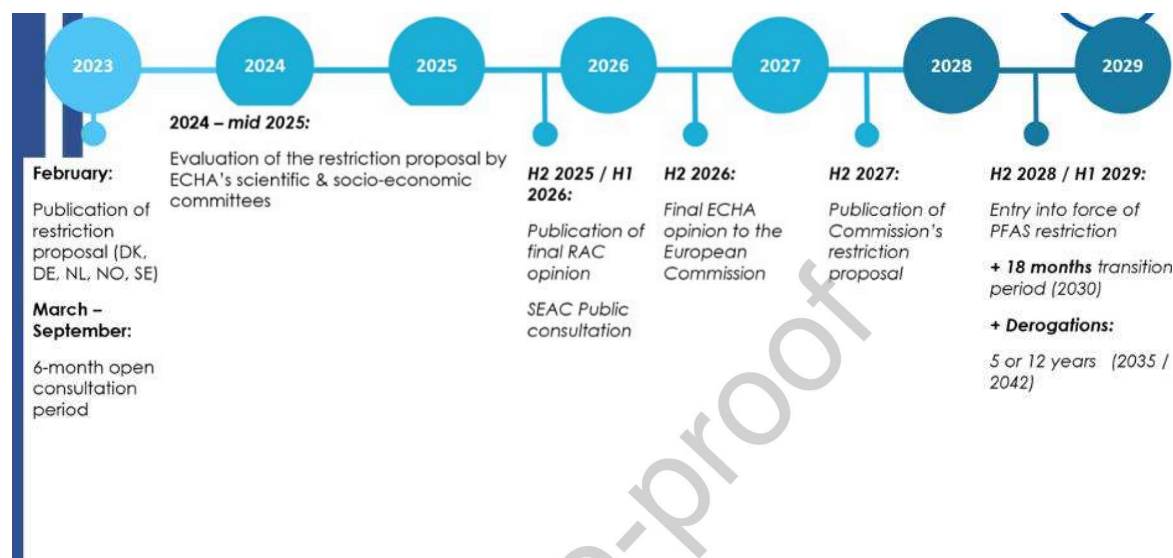


Fig. 73 : Timeline of the European Chemical Agency (ECHA) *versus* year (susceptible to be modified) [344].

Conclusions

PTFE is a safe material reaching quite high molar masses and is not currently subjected to regulatory restrictions. Thanks to its exceptional chemical, thermal, UV and aging resistance, waterproofness and moisture vapor permeability, PTFE is used in many advanced applications. As industries increasingly prioritize safety, operational efficiency and sustainability, PTFE's unique physicochemical properties, combined with continuous technological improvements, position this specialty polymer as a key material for next-generation of aerospace, electronics and medical technologies.

From the perspectives of decarbonization, circularity, risk prevention, reliability, durability and non-obsolescence, PTFE makes a substantial contribution to modern industrial systems. Its exceptional performance ensures its continued relevance, making it an irreplaceable material in many areas of daily life. PTFE components are incorporated into a wide range of products and devices, spanning diverse applications from industrial equipment to high-performance electronic systems and in medical apparatus.

Industrial sectors account for around 48 % of global PTFE consumption, while the electrical and electronic sectors represent approximately 22 %. PTFE market growth is particularly pronounced in the Asia-Pacific region, where PTFE-related industrial output increased by around 11% between 2022 and 2023, reflecting a strong demand driven by technological expansion and manufacturing growth. Thus, the global PTFE market size was valued at USD 3.63 billion in 2023 and is expected to reach USD 5.25 billion by 2030, growing at a Compound Annual Growing Rate (CAGR) of 5.5% from 2024 to 2030.

Although regarded as a PFAS under the OECD definition, PTFE meets the 13 PLC criteria. Following the first consultation on the PFAS dossier, which led to more than 5600 comments, a second public consultation on the PFAS restriction dossier is scheduled for spring 2026 was implemented and the consultation closed on May, 25th, 2026 (Fig. 73) [345]. 3511 comments from more than 250 individuals and 3200 organizations were submitted during the 60-day consultation on the draft opinion of ECHA's Committee for Socio-Economic Analysis (SEAC). Presently, SEAC is assessing the contributions and is expected to adopt its final opinion on the proposed restriction of PFAS by the end of 2026 [346]. Following this consultation Hence, numerous clarifications and regulatory decisions are expected that could significantly impact the future regulatory landscape for fluoropolymers.

Considering its exceptional properties, critical role in high-technology applications, and growing production, PTFE continues to maintain its high standard as a specialty polymer and remains an exceptional material. Many sectors, including medical technology, aerospace, car industries, optics and electronics, which require PTFE as a unique item, have begun to issue warnings if the ECHA's proposed ban is adopted, and it is expected that this material, like all FPs, will see more derogations.

Declaration of competing interest

The 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. No conflict of interest exists in the submission of this manuscript, and the manuscript is approved by all authors for publication. The manuscript has not been submitted or considered for publication elsewhere.

Credit authorship contribution statement

Saly Hawila: writing – original draft, methodology, formal analysis. **Jean-Pierre Habas:** writing – original draft, methodology, formal analysis, conceptualization, supervision. **Bruno Améduri:** writing – original draft, methodology, formal analysis, conceptualization, supervision.

Data availability

Data will be made available on request.

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