Ecotoxicity in Teflon's life cycle

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***Abstract*— Teflon is a non-stick material used in a wide range of products, including cookware, clothing, and surface coatings. However, Teflon can negatively impact both the environment and human health. Its ecotoxicity is an important issue that must be addressed to protect the environment from global warming compounds and to prevent potential health risks, such as reproductive problems. Some substitutes for Teflon are now available that have less impact on the environment and human health, and they are affordable for everyone.**

***Resumen*— El Teflón es un material antiadherente que se utiliza en una amplia gama de productos, incluidos utensilios de cocina, ropa y revestimientos de superficies. Sin embargo, el teflón puede tener efectos negativos tanto en el medio ambiente como en la salud humana. Su ecotoxicidad es un problema importante que debe abordarse para proteger el medio ambiente de los compuestos que provocan el calentamiento global y prevenir posibles riesgos para la salud, como problemas reproductivos. En la actualidad existen algunos sustitutos del teflón que tienen un impacto menor en el medio ambiente y la salud humana y son asequibles para todos.**

***Keywords*— Ecotoxicity, Teflon, PFAS, PFOA, TFA, polyfluoroalkyl**

I. Introduction

In 1938, polytetrafluoroethylene (PTFE), best known by its trade name as Teflon, was accidentally discovered by engineer Roy Plunkett (1910-1944) at DuPont in New Jersey [1]. PTFE is a synthetic polymer used in a wide range of products, such as kitchen utensils, clothing items, and industrial coatings for pipelines and molds.

PTFE is a thermoplastic polymer that belongs to the fluorocarbon family; it is a non-porous material (ideal for applications where non-stick properties are necessary) with high resistance to heat (withstanding temperatures up to 260 degrees Celsius without losing shape or degrading) and to abrasiveness (suitable for applications requiring erosion resistance, such as in products used in the aviation industry) [2].

II. Lifespan

A. Feedstock and Manufacturing

Tetrafluoroethylene (TFE) is a colorless, odorless gas that is polymerized to form PTFE. This can be achieved through free radical polymerization (the most common method, as it enhances the initial polymerization reaction) or coordination polymerization (in which TFE is polymerized in the presence of a coordination catalyst, though this is a less commonly used method). TFE may be derived from hexafluoroethane (C_2F_6) or perfluoroisobutene (C_4F_{10}), both synthesized with fluoride and other elements [3].

B. Lifespan

Teflon is considered a non-perishable material, meaning that due to its properties, it does not decompose or erode over time. Its ability to withstand high temperatures (up to 260°C/533 K/500°F), its resistance to UV rays (though limited to a few years), and its durability against chemical exposure (such as strong acids—sulfuric acid and hydrochloric acid—, bases like sodium hydroxide, known as caustic soda, and potassium hydroxide, as well as salts and solvents) allow this material to last for decades or even centuries with proper care [5].

If Teflon interacts with halogens (such as chlorine or fluorine), molten alkali metals (such as sodium or potassium), or oxidizing agents (such as hydrogen peroxide or nitric acid), its degradation and decomposition can be accelerated [6].

C. Final Disposal

Since PTFE is a non-biodegradable material, it must be managed responsibly at the end of its lifespan to avoid contamination. Currently, there are three methods for its disposal: incineration (producing carbon dioxide), recycling (with relatively low efficiency due to limited consumer awareness), and burial in a landfill (which may contaminate soil or groundwater if not done properly—by isolating it from other materials or burying it in locations without sun or water exposure) [7].

Companies that produce or use PTFE in various products must have a hazardous waste management plan, with an emphasis on collecting, storing, and transporting PTFE for proper disposal.

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III. ECOTOXICITY

Ecotoxicity refers to the ability of a chemical substance to harm living organisms, potentially altering organ function or even causing death in exposed individuals. Ecotoxicity is a significant concern, as it can negatively impact the environment by damaging molecular components or even entire ecosystem structures [8].

When ecotoxicity is studied in relation to humans, the terms toxicokinetics and toxicodynamics may arise. Toxicokinetics refers to the movement of toxins within the body, while toxicodynamics describes the interaction between toxins and cell receptors, often resulting in toxic effects [9].

The use of PTFE over time has attracted the attention of health agencies in various countries, as its contaminating effects have been observed not only in the environment but also in human [10].

A. *TFA – Trifluoro Acetic Acid:*

TFA is a colorless organic fluoride liquid with a vinegar-like odor [11]. It can be generated when PTFE undergoes thermolysis (a reaction in which a compound breaks down into at least two other compounds when exposed to high temperatures), producing polyfluorinated carboxylic acids and/or polychlorofluorides. These persistent compounds may accumulate in evaporative wetlands (evapotranspiration systems) as well as in the roots and seeds of plants within these environments. Currently, there is no evidence of any negative impact on plant health or germination success[12].

TFA is also a byproduct of PTFE production and can form from the degradation of other PFAS

B. *PFAS – Per-and Polyfluoroalkyl Substances:*

PFAS are a group of synthetic chemical compounds that are organofluorines, first used in the mid-20th century in products where their properties improved resistance to water [13]. Since the early 21st century, their impact and toxicity levels in humans and mammals have been studied. PFAS have been identified as persistent organic pollutants [14].

According to studies conducted by the National Academies of Sciences, Engineering, and Medicine (NASEM), exposure to PFAS is associated with a high risk of dyslipidemia (abnormal lipid (fat) levels in the blood, leading to cardiovascular diseases, commonly known as “high cholesterol”) [15].

Initially, PFAS were considered non-reactive; however, chemicals that disrupt hormones are now linked to a rapid decline in human fertility [16] and positive hepatic biomarkers in humans [17]. Studies have also found that exposure to PFAS influences the risk of developing hypertension during pregnancy, though it remains unclear whether such exposure is also connected to cardiovascular disorders during pregnancy [18].

Food and other consumer items are a major source of exposure to PFAS; however, water's role is highlighted here due to its high contamination levels. [19] Bioaccumulation and biomagnification of PFAS in marine species throughout the food web, particularly in fish and seafood that are commonly consumed, could have significant repercussions for human health. This is especially concerning since, with the high demand for PTFE, the disposal of PFAS-containing items in landfills and wastewater has disrupted ecosystem balance [20] [21].

Several mechanisms have been identified as harmful to human health and are linked to PFAS exposure. Examples include hypercholesterolemia (a condition characterized by the accumulation of high levels of cholesterol in the body), ulcerative colitis (a long-term condition that causes inflammation and ulcers in the colon and rectum), and thyroid diseases (such as hyperthyroidism, an endocrine disorder in which the thyroid gland does not produce enough hormones) [22] [23].

Due to a lack of high-quality epidemiological data and research on the relationship between PFAS and cancer, it is inconclusive to determine the connection between the two [24].

Since 2019, the European Council and the European commission [25] have developed an action plan to eliminate all non-essential uses of PFAS, based on the growing evidence of the negative effects caused by exposure to these substances. In the USA, certain PFAS are no longer manufactured, and as a result, they have gradually been phased out. Since 2020, the Food and Drug Administration – FDA [26] and manufacturers have reached an agreement to gradually eliminate certain types of PFAS used in food packaging by 2024.

Despite efforts to eliminate PFAS, the disposal of PFAS in water has had a significant impact. It is estimated that in the USA alone, there are more than 25,000 PFAS-contaminated sites, and at least 6 million Americans' drinking water contains PFAS, according to the Environmental Protection Agency (EPA) [27].

C. *PFOA – Perfluorooctanoic Acid:*

Also known as C8 (due to its 8-carbon chain structure), PFOA is a perfluorinated carboxylic acid used worldwide as an industrial surfactant (a substance that affects surface tension at the contact interface of two phases). It is used in products such as water repellents, fabric oils, leather, and waxed paper. PFOA has been produced in industrial quantities since the 1940s [28].

Just like PFAS, the disposal of contaminated wastewater has been a major source of industrial contamination of this acid in the environment. However, there are other sources of contamination, such as food packaging. For example, microwave popcorn packaging [29] may contain fluorotelomers—a non-desirable byproduct in the formation of PFOA—and contact paper, which is lipophobic (designed to

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prevent oil from penetrating the packaging). Studies suggest that consuming as many as ten bags per year could result in PFOA levels reaching approximately 20% of those measured in consumers.

PFOA is potentially carcinogenic, a possible hepatic toxin, and toxic to the immune system. It also affects hormones and can alter thyroid hormone levels, leading to higher concentration [30][31]. Research has shown that PFOA is resistant to degradation through natural processes such as metabolism (the physical and chemical processes by which the body transforms and/or uses energy), hydrolysis (a chemical reaction in which water molecules break chemical bonds to form new species), photolysis (the breaking of chemical bonds due to radiant energy), and biodegradation (the breakdown of organic matter by microorganisms). As a result, it is long-lasting in the environment [32].

Since 2015, there has been a proposal to include PFAO in the Stockholm Convention on Persistent Organic Polluters [33]. However, this acid is still in use today, particularly in new products such as fire-fighting foams, due to its physicochemical properties during use [34].

D. PFOS – Perfluorooctanesulfonic Acid:

PFOS is a chemical compound that has been produced since 1949 and used in a variety of products, similar to PFAS and PFOA. It is a substance with high resistance to degradation and is long-lasting in the environment [35]. PFOS is commonly used in fire protection products such as foams, due to its hydrophobic and lipophobic properties, which prevent it from adding polarity, unlike other sulfonic acids [36].

To date, there is evidence of the effects PFOS has on humans in areas such as reproductive health [37] [38], development, and impacts on the liver, kidneys, thyroid, and immune system [39].

Similar to PFAS and PFOA, contaminated wastewater disposal is a major source of industrial pollution in the environment [40]. PFOS has been linked to significant public health issues related to infertility, such as delayed conception and reduced pregnancy success in women, as well as lower sperm count and a decrease in the number of morphologically normal sperm in men. Additionally, PFOS is associated with reduced testosterone levels and thyroid diseases (it alters thyroid hormone levels in adults), as well as hypercholesterolemia [41] 42].

PFOS is the first substance that, through research, has been linked to the development of Attention Deficit Hyperactivity Disorder (ADHD) [43] [44].

PFOA and PFOS are specific types of PFAS that have been extensively studied and regulated due to their environmental persistence and potential health risks.

IV. CURRENT STATE

The development of the world's population has led to the creation of substances known as “forever chemicals,” which have started to show health effects or indications in recent decades—some unfortunately more severe than others.

In the case of PTFE and its derivatives, the widespread use and harmful effects of these substances necessitate their replacement with non-fluorinated alternatives, especially in regions where they are still used and where there are no regulations or bans on their use.

The substances discussed in this article have been tested in laboratories due to the concerns they raise within the community. So far, the International Agency for Research on Cancer (IARC) has classified some PTFE derivatives, such as PFOA, as “carcinogenic to humans” (Group 1), based on sufficient evidence that it can cause cancer in laboratory animals and strong evidence that it has carcinogenic properties in humans exposed to it. Additionally, IARC has classified PFOS as “possibly carcinogenic to humans” (Group 2B), based on strong evidence that it exhibits some key properties of a carcinogen in humans exposed to it, and limited evidence that it may cause cancer in laboratory animals [45][46].

V. DAY-TO-DAY RECOMMENDATIONS

Teflon coatings in kitchen items need special care to avoid impacting human health. However, few people are aware of the dangers associated with improper handling. The following recommendations are provided in case, for any reason, a Teflon-coated product must be used [47]:

- Handle your Teflon-coated utensils with non-corrosive materials, such as wood or silicone.
- To avoid inhaling toxic fumes, it is advised to cook with the air extractor (ventilation hood) on.
- Avoid using Teflon-coated utensils when preparing food at temperatures exceeding 260°C. Use alternatives, such as cast iron, which can withstand temperatures up to 500°C.
- Properly dispose of worn-out products to avoid ingestion of the material.
- Replace Teflon-coated utensils with safer and more eco-friendly options, such as ceramic coating, stainless steel, or cast iron.
- When purchasing non-stick utensils, research the product to ensure it is free of PFAS, PFOA, or TFA.
- Cure all Teflon-coated utensils before using them for the first time

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