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Key Challenges in Regulation of Per- and Polyfluoroalkyl Substances - PFAS

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ABSTRACT

Per- and polyfluoroalkyl substances (PFASs) are a class of synthetic chemicals characterized by their resistance to heat, water, and oil, making them invaluable across various industries. Despite their utility, these chemicals pose significant environmental and public health risks because of their durability and resistance to degradation. PFASs are highly persistent in the environment, leading to accumulation in water systems, wildlife, and humans, potentially causing various health issues, including cancer, developmental delays, and immune system disorders. Their ability to bioaccumulate and travel through water systems makes them a concern for drinking water contamination and food chain exposure. The global distribution of PFASs, even reaching remote areas, highlights their pervasive nature. This review paper aims to address challenges in PFAS regulation, as well as the environmental and health damages they cause. Exploring the nuances of PFAS regulation is crucial, since there are numerous types of PFASs, each with different industrial and consumer applications, impacts, and risks. A blanket ban on all PFASs is not feasible due to their varied uses and the complexity of their impacts. Instead, it is necessary to create a targeted and refined regulatory approach that considers the specific characteristics and uses of different PFASs—promoting safer alternatives where possible and necessary. Effectively addressing the pervasive presence and damage of PFAS will require a holistic strategy encompassing public education, appropriate restrictions, innovation in safer alternatives, and a commitment to circular economy principles to mitigate their impact on both public safety and the environment.

Introduction

Per- and polyfluoroalkyl substances (PFASs) encompass a diverse group of synthetic chemicals that play a crucial role in numerous global industries, such as textiles, food packaging, lubrication, refrigeration, and electronics. These substances are highly valued for their durability, thanks to the robust carbon-fluorine bonds that define their molecular structure. Renowned as one of the strongest bonds in organic chemistry, the carbon-fluorine bond grants PFASs exceptional resistance to environmental degradation, whether through natural processes or human interventions.

While the resilience of PFASs is advantageous for industrial purposes, it presents significant challenges for the environment and human health. These chemicals are persistent and do not easily break down, leading to their accumulation in the environment and living organisms over time. It is important to note that PFAS compounds exhibit a wide range of behaviors in the environment and health effects. Some PFAS polymers can have half-lives of up to 1,000 years in soil, while certain non-polymer PFASs can persist for over 40 years in water. Without stringent measures to manage and reduce certain PFAS emissions, the levels of environmental and biological accumulation will continue to rise.

It's crucial to recognize that PFAS chemicals vary significantly in their composition and associated health risks. Some classes of PFAS exposure pose severe and potentially irreversible health dangers. Notably, non-polymer PFAS compounds such as PFOS and PFOA have undergone extensive research, demonstrating links to various health problems, including cancer, thyroid disorders, and developmental delays in children. These smaller molecule PFASs tend to disperse widely in the environment and infiltrate the food chain, which results in bioaccumulation and increased exposure risks. In contrast, larger molecule PFAS polymers are generally more stable and less prone to entering biological systems.

Despite the wealth of research on certain PFASs, comprehensive data on the full spectrum of these chemicals, particularly their complex mixtures, remains limited. This lack of detailed information poses challenges for regulatory bodies tasked with evaluating and mitigating the risks associated with PFAS exposure. Regulations must be able to differentiate between the different types of PFASs, especially between polymer and non-polymer forms, to effectively address the specific risks posed by each group.

In this review, I aim to advocate for a practical approach to regulating and managing various PFAS compounds based on their environmental persistence, potential health risks, essential utility in serving mankind in the absence of viable alternatives, and a risk-based regulatory approach. Addressing the challenges posed by PFASs will require a multifaceted strategy involving scientific research, regulatory measures, and international cooperation. Only through such comprehensive efforts can we effectively manage the risks associated with these persistent chemicals and protect both human health and the environment.

The Origins of PFAS: A Historical Overview

PFAS chemicals have been integral to the chemical industry for over seven decades, beginning with the synthesis of polychlorotrifluoroethylene (PCTFE) by Fritz Schloffer and Otto Scherer at IG Farben in 1934. This marked the inception of a group of chemicals renowned for their diverse applications across industries such as textiles, food packaging, and electronics. Initially commercialized as Kel-F by M.W. Kellogg in the 1950s and later produced by 3M until 1996 (when manufacturing rights were transferred to Daikin Industries, now known as Neoflon). PFASs resistance to heat, water, and oil, revolutionized manufacturing processes worldwide.

However, PCTFE solely served as the precursor to the more renowned 'forever chemical' PTFE, also known by its trade name Teflon, which revolutionized industries with its non-stick properties. While working for E.I. du Pont de Nemours & Co. in 1938, J. Plunkett accidentally discovered PTFE. Although Teflon initially fulfilled critical roles during World War II's Manhattan Project where it was crucial in fabricating materials for handling hazardous materials, Teflon's post-war applications expanded significantly under DuPont's stewardship. Following World War II, a period of profound technological and industrial innovation unfolded as nations aimed to rebuild and progress beyond the devastation and economic slowdown of the war years. In 1946, DuPont announced the construction of a plastics plant in Parkersburg, West Virginia, signaling the dawn of a new era in PFAS manufacturing. By 1951, this facility was producing Teflon, marking the beginning of its integration into cookware, fabric and textile stain repellents, and industrial coatings.

In 1952, prominent publications like Popular Mechanics played a key role in disseminating these technological breakthroughs to the wider public. They emphasized the transformative potential of fluorocarbons, showcasing applications that seemed almost futuristic at the time. This excitement was well-founded, as fluorocarbons exhibited a range of highly desirable properties across various sectors.

One of the most notable applications was as a lubricant for car engines, with the promise of lasting a lifetime. The exceptional durability and stability of fluorocarbons under high temperatures and pressures made them ideal for such uses, significantly reducing the need for frequent lubricant changes and maintenance.

In the household products domain, the concept of fire-resistant house paint and non-stick cookware was particularly compelling. Fire-resistant paint aimed to improve home safety by reducing the risk of fire damage, while non-stick cookware utilized the unique properties of Teflon to create surfaces where food would not adhere, simplifying both cooking and cleaning processes.

Teflon, developed by Chemours (formerly part of DuPont), became synonymous with non-stick cookware and was one of the first widespread commercial applications of PFAS. Its success led to a plethora of other applications, such as waterproof clothing, which benefited from PFAS's water-repellent properties, and personal care products, where their unique characteristics enhanced the performance of cosmetics and other items.

Sociologist Rebecca Altman reflects on Teflon's development, highlighting the crucial collaboration and significant public investment that brought this groundbreaking material to the market. The history of PFAS is a testament to the confluence of chance discoveries, deliberate actions, and innovative advancements that have shaped their evolution and widespread adoption. This narrative not only showcases the transformative journey of fluorocarbons but also underscores their far-reaching impact across various industries, demonstrating their pivotal role in shaping modern society. The enduring presence of PFAS in the chemical industry serves as a testament to human ingenuity and technological progress. As concerns about environmental and health challenges associated with PFAS continue to grow, it is essential to acknowledge the intricate history and profound influence of these classes of chemicals on society, and to consider the need for responsible management and mitigation strategies to ensure their continued use does not compromise our collective well-being.

Two Main Classes of PFAS Chemicals

PFAS represents a diverse collection of chemical compounds characterized by strong carbon-fluorine bonds, which are among the strongest in organic chemistry. Broadly, PFAS can be categorized into two main classes: polymers and non-polymers, each differing significantly in their chemical structure, use, and environmental impact.

Polymer PFAS are composed of long chains containing many repeating units, each made up of a backbone of carbon atoms fully or partially surrounded by fluorine atoms. These substances are typically large molecules with high molecular weights. Due to their size and complex structure, they are generally less mobile and have lower bioavailability, meaning they are less likely to be absorbed by living organisms. This characteristic often leads industries to classify polymer PFAS as being of "low concern" regarding immediate toxicity or potential for bioaccumulation. Notable examples of polymer PFAS include polytetrafluoroethylene (PTFE), commonly known by the brand name Teflon, and Polyvinylidene fluoride (PVDF), used in applications requiring high purity and resistance to solvents, acids, and bases.

In contrast, non-polymer PFAS are smaller, non-polymeric molecules that usually consist of a carbon chain ranging from 2 to 13 carbon atoms in length. These compounds are more reactive and mobile than their polymeric counterparts, making them more likely to be absorbed by organisms and to disperse through environmental mediums such as air and water. Non-polymer PFAS are known for their ability to persist in the environment and bioaccumulate in the tissues of living organisms, including humans, where they can pose significant health risks. Prominent examples of non-polymer PFAS include perfluorooctanoic acid (PFOA) and perfluorooctane sulfonate (PFOS), both of which have been linked to various adverse health effects, such as developmental issues, liver and kidney disease, and immune system disruptions.

Understanding the distinctions between these two classes of PFAS is crucial for assessing risks and managing the environmental and health impacts associated with their use and disposal.

PFAS Life Cycle Through the Environment

Due to their extensive use and chemical stability, PFAS often enter the environment through multiple channels, leading to widespread contamination and raising significant concerns for both ecosystem and human health. Figure 1 illustrates various pathways for PFAS entering the environment.

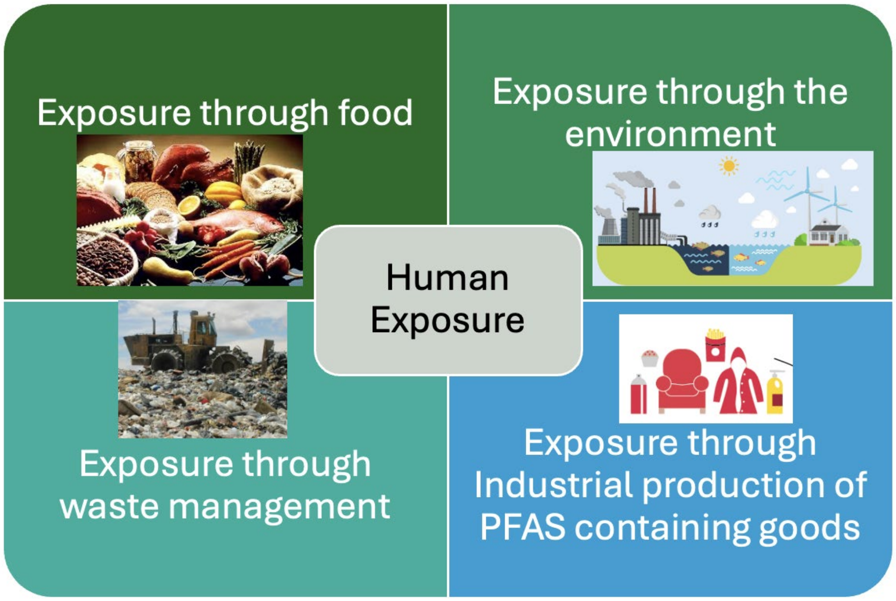

Figure 1. Typical PFAS pathways

One major pathway for most PFAS environmental entry is through industrial discharges. Factories that produce or use PFAS can release these chemicals into the air and water during production processes, directly impacting local air and water quality. Landfills also significantly contribute to PFAS contamination. Products containing PFAS, such as non-stick cookware, water-repellent clothing, and food packaging, often end up in landfills. Over time, PFAS can leach from these products into landfill leachate, a liquid which can eventually contaminate groundwater or surface water bodies. Wastewater treatment plants (WWTPs) are an additional source of PFAS release. Typically, WWTPs are not designed to remove PFAS from sewage, so treated effluent may still contain significant levels of these chemicals. When this effluent is discharged into rivers or oceans, it can contaminate aquatic environments.

Upon release into the environment, PFAS can undergo various processes depending on their structural nature, which can facilitate their spread across different mediums. In aquatic environments, certain non-polymer PFAS have the potential to accumulate in organisms and increase in concentration up the food chain. This bioaccumulation occurs when the rate of uptake exceeds the organism's ability to metabolize and excrete the substance. Additionally, biomagnification refers to the progressive increase in substance concentration as it moves up the food chain, posing significant risks to both aquatic life and humans who consume contaminated fish and shellfish.

Furthermore, it is noteworthy that some PFAS can undergo volatilization into the atmosphere under specific conditions, enabling their transport over extended distances away from their initial source of contamination. This atmospheric transport mechanism can result in the deposition of PFAS in areas distant from any direct sources of pollution, thereby expanding the geographical extent of contamination and complicating efforts to manage and mitigate PFAS-related environmental and health risks.

The pervasive presence and enduring nature of certain PFAS in the environment, along with their tendency to bioaccumulate in living organisms and present health hazards, underscore the urgent need to tackle PFAS contamination. This can be achieved through the implementation of improved, risk-based regulatory frameworks, the adoption of proactive pollution prevention strategies, and the advancement of efficient remediation technologies.

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PFAS Impact on Health

A growing body of evidence suggests that PFAS exposure is linked to a range of adverse health effects. Once ingested or inhaled, certain classes of PFAS are capable of persisting in the body due to their tendency to bind to serum proteins, including albumin in blood plasma. This binding mechanism likely explains their accumulation in tissues with high blood flow, such as the liver and kidneys.

Non-polymer PFAS exposure is associated with several negative health outcomes in humans, including elevated cholesterol levels, an increased risk of developing diabetes, disruption of endocrine and immune system function, an elevated risk of certain types of cancer. Figure 2 illustrates the possible health impact of PFAS exposure to human health.

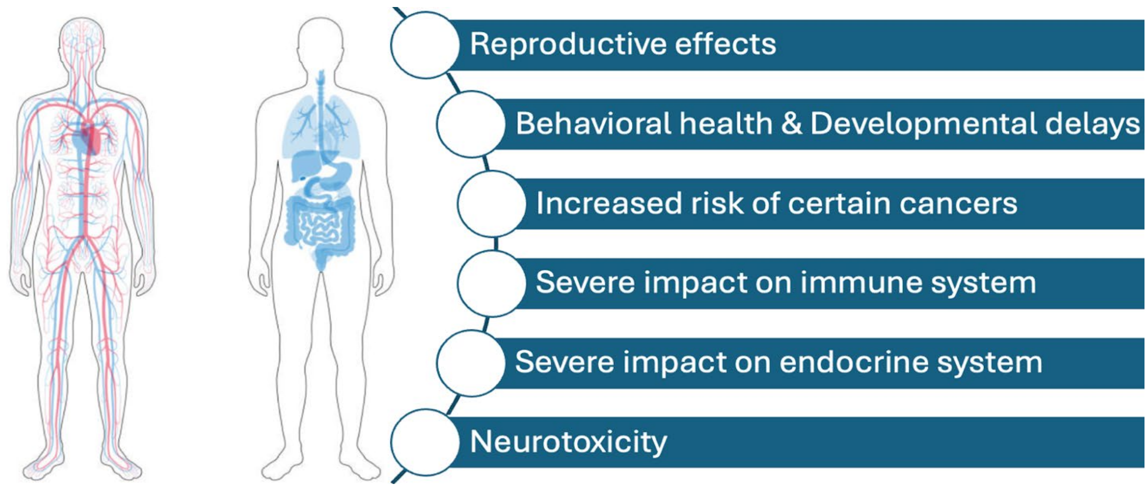

Figure 2. Impact of PFAS on human health.

Furthermore, non-polymer PFAS have been linked to diminished vaccine efficacy in humans, highlighting the need for further research into their impact on human health.

According to a report by the Centers for Disease Control and Prevention (CDC) a staggering 99% of Americans have detectable levels of PFAS in their blood. This widespread contamination is a concern, as it suggests that exposure to these toxic chemicals is pervasive, meaning a significant number of people are likely experiencing side effects due to this widespread exposure.

In animal studies, the evidence is even more concerning. Exposure to non-polymer PFAS has been shown to cause reproductive and developmental defects, as well as an increased incidence of tumors. Additionally, these PFAS have been linked to dysfunction in the liver, kidney, and immune system in animal models.

While researchers are actively working to elucidate the underlying chemistry behind these negative health impacts, the available evidence suggests that non-polymer PFAS pose a significant threat to human health. In contrast, fluoropolymers, due to their large molecular structure, do not pose the same risks as they do not bioaccumulate or exert toxic effects.

Differing from non-polymer PFAS, fluoropolymers are large molecule PFAS that are not readily bioavailable and are not known to cause health impacts because they cannot enter biological systems. Fluoropolymers, such as PTFE, are normally regarded as safe for human health due to their limited bioavailability. While concerns exist about potential environmental contamination during their production and disposal, fluoropolymers themselves do not significantly contribute to the release of smaller PFAS molecules into the environment.

The Term "Forever Chemical" is a Misnomer

The term "forever chemical" is a misleading label, according to Christopher Higgins, a leading expert on PFAS and a distinguished professor at the Colorado School of Mines. He pointed out that chemicals like PFOS, PFOA, and PFHxS are commonly referred to as such due to their persistent nature and resistance to degradation over time. These substances fall under the category of perfluorinated compounds, unlike other PFAS varieties that are more susceptible to breakdown and transformation. Thanks to recent advancements in remediation technologies, there has been significant headway in breaking down these resilient substances, which were once believed to last for centuries in their original form.

The structural differences among PFAS compounds play a crucial role. Broadly, all PFAS consist of a chain of carbon atoms bonded to fluorine atoms. In some molecules, known as per-fluorinated, every carbon-hydrogen bond is replaced by a fluorine atom, while in others, termed poly-fluorinated, only some of these bonds are replaced. According to Higgins, this variation is akin to a "crack in the molecule's armor," making those with partial fluorination more likely to degrade under environmental conditions. Many polyfluoroalkyl substances do indeed transform in the environment.

Higgins noted that the less stable PFAS, which can degrade, often serve as precursors to perfluoroalkyl acids. For instance, fluorotelomer alcohols found in firefighters' gear can degrade in the environment and eventually form PFOA among other compounds.

Ongoing scientific investigations are focused on understanding the breakdown products of these PFAS and the implications thereof. The oversimplification of labeling all PFAS as "forever chemicals" overlooks the complex reality that these chemicals can degrade into various substances, with outcomes that could be either more or less harmful, depending on the degradation agents involved, such as bacteria, oxygen, or heat.

Advances in PFAS Remediation Technologies

The remediation of PFASs in environmental settings has become increasingly imperative due to the persistent nature of these chemicals and their potential toxicological impacts on wildlife and human health. PFASs are known for their resistance to degradation, making them exceedingly difficult to eliminate using conventional water treatment methods. This challenge is exacerbated by the high costs associated with the effective remediation techniques currently available, which often involve substantial energy consumption and significant capital and operational expenditures. Consequently, despite promising results in laboratory settings, the application of most remediation techniques in real-world scenarios remains limited.

Attached Figure 3 lists out advanced remediation techniques that show potential for broader application across various classes of PFASs, including the challenging removal of short-chain compounds. Techniques such as electrochemical methods, sonochemical processes, advanced oxidation processes (AOPs), and plasma treatments, along with innovative hybrid approaches, are scrutinized for their ability to address both long-chain and some short-chain PFASs, as well as the particularly resilient perfluoroalkyl acids (PFAAs).

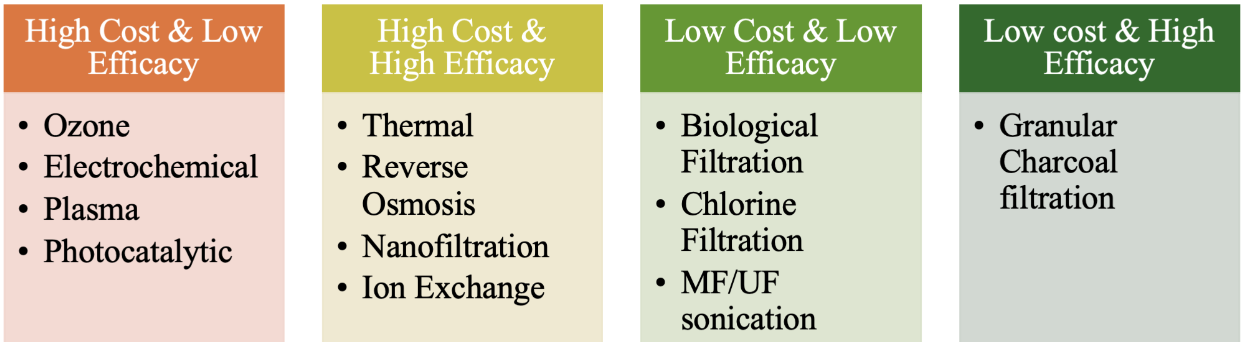

Figure 3. PFAS Remediation techniques

An integrated approach, combining multiple effective treatment methods within a single processing unit, could potentially revolutionize PFAS remediation. Such an approach would not only enhance the efficiency of the removal process but also ensure its applicability across different environmental contexts. Additionally, considering site-specific water quality parameters and integrating community perspectives can enhance the viability and acceptance of these technologies in practical field applications, thereby providing a comprehensive solution to the pervasive issue of PFAS contamination.

Pragmatic Frameworks for Regulation of PFAS Chemicals

Regulating PFAS poses a multitude of intricate challenges, necessitating a holistic approach that combines state-of-the-art scientific methodologies with a collaborative decision-making process. One of the key obstacles lies in the significant gaps in data and uncertainties surrounding the toxicology of the numerous PFAS chemicals, with more than 4,700 variants identified thus far. For example, a recent study conducted by the US Environmental Protection Agency (EPA) revealed that only a mere 4% of PFAS compounds have undergone toxicity testing, leaving the majority with unknown impacts on human health and the environment.

Another notable challenge stems from the limited information available on the actual exposure levels to different classes of PFAS in both the environment and human bodies. As per a study published in the journal Environmental Science & Technology, only approximately 10% of PFAS compounds, predominantly non-polymeric PFAS, have been detected in human blood samples. This underscores the necessity for more comprehensive monitoring and measurement techniques. The scarcity of data impedes the ability of scientists and regulators to accurately assess the risks associated with specific PFAS exposure and devise effective management strategies.

To effectively tackle these challenges, a cooperative and pragmatic strategy is essential, requiring the engagement of scientists, regulatory bodies, policymakers, industry representatives, and the public. The regulatory framework should be guided by two principal concepts: risk-based and essential use-based regulation. This method focuses on prioritizing actions against PFAS chemicals that present the most significant risks to human health and the environment. It also recognizes the indispensable role of certain PFAS chemicals in high-value applications like medical devices, Solar and wind energy, energy storage and PEM electrolysis, where alternatives are currently not feasible over the short term.

For PFAS chemicals with available data, scientists should perform risk assessments to determine their potential impacts on health and the environment. However, the determination of what constitutes an 'acceptable risk' should not rest solely with scientists. Rather, it should result from a comprehensive dialogue involving regulatory authorities, policymakers, industry stakeholders, and the public. This inclusive approach to decision-making is crucial for devising effective and widely accepted strategies for managing the risks associated with PFAS chemicals. Figure 4 presents a risk-based regulation proposal from the Royal Society of Chemistry – UK, exemplifying this approach.

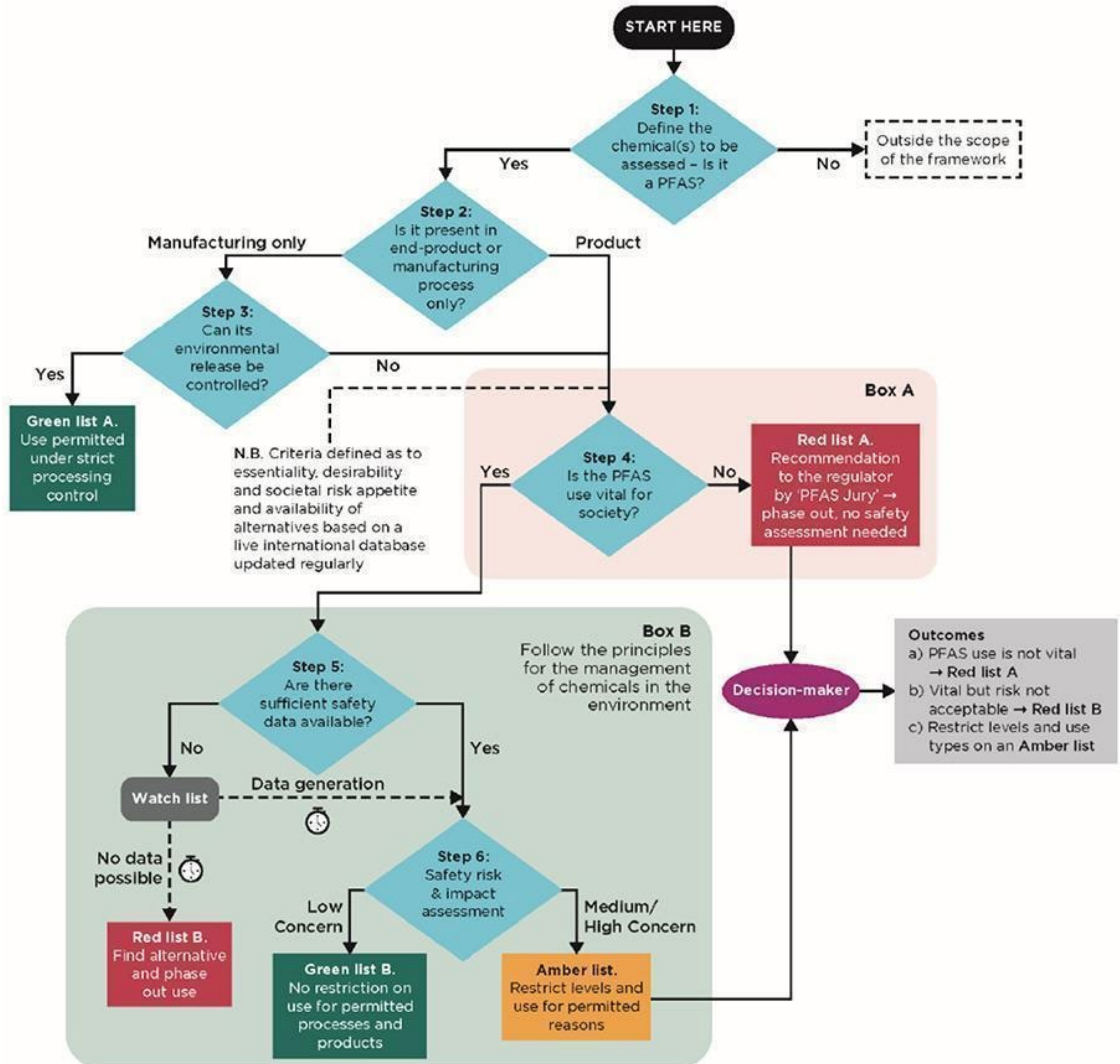

Figure 4. Example of risk-based regulation proposal by Royal Society of Chemistry. UK.

The concept of risk-based regulation is crucial. However, it is essential to recognize that risk-based regulation can be overruled by broad bans, which may not be scientifically justified. Instead, decisions on what constitutes an "acceptable risk" should be based on established scientific definitions and involve a broader dialogue that includes regulatory authorities, policymakers, industry stakeholders, and the public. One such example is the European Commission's proposed approach to regulating PFAS chemicals, which is overly broad and treats bioavailable and non-bioavailable PFAS identically. The proposal bans most uses with limited exemptions, which is not pragmatic nor scientifically justified. Essential use should be determined by a nuanced understanding of the chemical risks and benefits across various sectors, considering the complex interplay between chemical use, human health, and environmental protection.

While some uses of hazardous substances are deemed essential for critical applications such as climate change mitigation and health protection, the strategy emphasizes substitution wherever possible to align with key policy objectives. By finding safer alternatives to these harmful chemicals, the strategy seeks to protect both human health and the environment. This comprehensive approach recognizes the importance of transitioning towards non-toxic material cycles that prioritize sustainability and public health.

The incorporation of essential use into legislation carries significant legal weight, requiring careful evaluation of feasibility and criteria for acceptable alternatives. Sector-specific regulations, objectives, needs, and unique aspects must be considered to effectively implement this concept. For instance, in the medical sector, prioritizing essential use ensures the continued availability of life-saving medicines and medical devices. For example, the development of new antibiotics requires the use of certain chemicals that are essential for their production. Conversely, in consumer products such as waterproofing fabrics and non-stick cookware, finding suitable alternatives to hazardous chemicals is relatively simpler. The strategy aims to promote a shift towards a more environmentally friendly and health-conscious approach to chemical use by encouraging the transition to safer practices and incentivizing the use of sustainable alternatives.

A notable example is the replacement of perfluorooctanoic acid (PFOA) and perfluorooctane sulfonate (PFOS) with safer alternatives in non-stick cookware. These PFASs have been linked to adverse health effects, including cancer and reproductive issues. The EU has banned the use of these chemicals in food contact materials, and companies are transitioning to safer alternatives such as ceramic coatings or silicone-based non-stick coatings.

The effective implementation of essential use requires a nuanced understanding of the chemical risks and benefits across various sectors. By considering the complex interplay between chemical use, human health, and environmental protection, policymakers can develop targeted solutions that balance competing interests while driving innovation towards increased sustainability. Policymakers do not have the sufficient expertise to create blanket bans themselves, Instead, scientists and industry experts in the field should provide evidence for regulatory actions, while policymakers should mainly serve as facilitators of the regulatory process, ensuring that decisions are informed by the best available scientific evidence.

Need For Holistic Approach

The effective management of PFAS requires a holistic strategy that integrates multiple solutions. This multifaceted approach must include education on the necessary uses and associated risks associated with these chemicals, pragmatic regulation to limit their use and release, fostering innovation for safer alternatives, and embracing circular economy concepts to mitigate the widespread impact of these persistent pollutants on human health and the environment. Table 1 lists out potential range of strategies and specific actions regulatory authorities can take for holistic regulations of PFAS for next decades.

Table 1. Strategies and Specific Actions for holistic regulation.

Strategy	Specific Actions
Implementing pragmatic, risk-based regulations based on the principles of essential use.	Enforce regulations on the production and use of PFAS to prevent environmental contamination and human exposure.
Establishing international agreements	Create global treaties to ban PFAS chemicals in consumer products and non-essential industrial processes.

Developing standardized testing and monitoring	Set up methods and programs to track forever chemicals in air, water, soil, and food.
Encouraging research in alternatives	Promote innovation in materials and technologies that avoid the use of forever chemicals.
Collaborating with industry	Work with stakeholders to progressively eliminate forever chemicals and adopt safer alternatives.
Providing incentives for sustainable practices	Assist businesses in their pursuit of sustainability and in steering clear of persistent chemicals.
Educating the public	Increase awareness about the risks of forever chemicals and promote informed consumer choices.
Enforcing penalties for non-compliance	Apply fines and penalties to ensure adherence to regulations on forever chemicals
Investing in remediation technologies	Fund research and development to clean up contaminated sites and reduce the impact of forever chemicals.
Engaging in international cooperation	Share best practices and coordinate global efforts to regulate forever chemicals.

Raising awareness about PFAS is crucial for empowering individuals to make informed decisions about these chemicals. Educational programs must emphasize the uses, importance, hazards, and risks associated with PFAS to ensure that consumers are equipped with the knowledge necessary to navigate the complexities of PFAS use. Global forums and international cooperation can facilitate the sharing of knowledge and best practices, ultimately fostering a more informed and empowered global community. Well-informed consumers are more likely to make choices that prioritize their health and the environment. This growing demand for non-toxic products can significantly influence industry behavior, encouraging companies to adopt better practices and innovate towards safer alternatives.

Regulation plays a vital role in addressing PFAS contamination. Science-based frameworks and societal impact assessments can create workable legislation that balances safety with innovation. Effective regulation can ensure that measures are in place to limit PFAS use, mitigate environmental contamination, and promote sustainable development.

Innovation is essential for developing technologies and processes that minimize PFAS exposure and develop safer alternatives with equivalent or improved functional benefits. Investing in research and development can drive progress towards safer solutions that reduce the risks associated with PFAS.

Table 2. Circular economy approaches for two classes of PFAS

Non Polymeric PFAS	• Safe and sustainable by design. Alternate material selection. • Prevention/elimination of substances of concern from the design phase.
Polymeric PFAS	• Collaboration to facilitate a safe circular economy: from production to processing to end of life. • Track, Manage and Monitor substances through end of lifecycle.

	• Removal of PFAS substances during the recycling process. • Reuse of PFAS substances. Prevention of risks to humans and the environment when reusing materials containing substances of concern

Adopting a circular economy approach is critical for addressing the long-term challenges posed by PFAS. Depending upon risks associated with a specific class of PFAS, a different approach to sustainability may be needed. Table 2 illustrates this approach. It involves considering safe alternatives designs, sustainable end-of-life solutions, life cycle assessments to understand environmental impacts, and promoting sustainable practices throughout the entire product lifecycle. Challenging the use of persistent and toxic PFAS and embracing sustainable solutions prioritizes sustainability and public health.

Conclusion

This review adopts a multi-faceted strategy to mitigate the adverse effects of per- and polyfluoroalkyl substances (PFAS), recognizing that sweeping, blanket bans may prove to be counterproductive. It is essential to distinguish between polymeric and non-polymeric PFAS, as they differ significantly in their environmental and health impacts. Addressing the challenges posed by PFAS requires a comprehensive approach that encompasses public education, the setting of regulatory limits, industry engagement, the promotion of innovation in developing safer alternatives, and a commitment to circular economy principles. Given the pervasive use and impact of PFAS, this review calls for a globally coordinated, risk-based regulatory framework, the development of safer substitutes, and collaborative scientific efforts to eradicate PFAS from the environment.

Proposed solutions include prioritizing research into alternative technologies and materials that can replace PFAS without sacrificing performance or functionality. Simultaneously, it is crucial to address PFAS contamination already in the environment to manage existing pollution effectively and reduce continual risks to environmental and public health. Conducting life cycle assessments to comprehend the full environmental impact of PFAS, investigating the health risks associated with PFAS exposure, and formulating effective mitigation strategies are imperative. International cooperation and the sharing of knowledge are essential to tackle the global challenge of PFAS pollution.

Regulating PFAS is challenging, largely due to the vast number of compounds and limited toxicological data. A collaborative effort involving scientists, regulatory agencies, and the community is crucial for effective risk management. Promoting a shift towards a more sustainable and circular economy will help lessen the negative impacts of PFAS contamination on health and the environment.

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