

PFAS Regulations and Economic Impact: A Review of the U.S. and European Food and Pharmaceutical Industries with Some Case Studies

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ABSTRACT

Background: Per- and polyfluoroalkyl substances (PFAS) are synthetic substances broadly incorporated into food ingredients and packaging, pharmaceuticals, textiles, industrial uses, and electronics. Their stability makes them difficult to break down and retain in the environment. PFAS have been documented to “accumulate in organisms and have adverse health effects.” PFAS are a growing environmental and health concern and a focus of regulatory agencies in the United States and the European Union. Different regulatory approaches have resulted in measurable economic impacts.

Objective: This review focuses on regulatory differences of PFAS in the United States and the European Union and their economic implications for the food and pharmaceutical sectors. It highlights the influence of regulatory differences on business compliance, innovation, supply chains, and long-term environmental protection.

Methodology: This review analyzed primary literature published between 2010 and 2026. Regulatory and scientific literature from USEPA, ECHA, EFSA, and scientific databases including ScienceDirect, PubMed, and Web of Science was utilized. A comparative analysis was employed to assess regulatory and economic implications.

Results: The assessment shows evident differences between U.S. and EU PFAS regulatory frameworks. The EU follows a precautionary and class-based regulatory method within REACH that supports early-stage risk prevention and sustainable development. The U.S. largely follows a risk-based and chemical-specific approach, which may reduce short-term compliance burdens but result in higher long-term costs associated with litigation, risk remediation, and exposure prevention. The food sector faces contamination, reformulation, recall, and traceability issues, while the pharmaceutical sector faces substance changes, manufacturing, and compliance issues.

Conclusion: Precautionary regulation may provide greater long-term benefits for human health and environmental protection despite higher initial business costs. Harmonized global PFAS regulation, research funding for safer alternatives, and engagement among policymakers, researchers, and businesses can protect the environment, improve human health, and support sustainable economic development.



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1. Introduction

1.1. Emergence of PFAS as a Global Environmental Governance Challenge

Per- and polyfluoroalkyl substances (PFAS) are synthetic chemicals that have been commercially produced since the 1940s because of their resistance to heat, water, and

chemical degradation. This resistance has resulted in the use of PFAS in industrial and commercial applications in food packaging, textiles, electronics, and many other industries. PFAS are even contained in consumer products. Although they have undergone considerable use since the 1940s, environmental and industrial advancements have outpaced the production of these chemicals (Buck *et al.*, 2011).

PFAS have also become a leading environmental issue of the 21st century. The strength of the carbon-fluorine bond makes these compounds exceptionally persistent. As such, PFAS do not naturally degrade. They contaminate the environment for decades and are dubbed “forever chemicals.” PFAS are widespread and persistent contaminants of the environment, having been detected in human blood, breast milk, drinking water, food, wildlife, and even products (Sunderland *et al.*, 2019; Wang *et al.*, 2017).

The ubiquitous nature of PFAS globally has made the public fairly concerned about the sustainability of the environment and the safety of the public. Because they are persistent, people are continuously exposed to them via contaminated drinking water, food, consumer products, and through work. In response, PFAS have been classified by governments, environmental organizations, and regulatory bodies more and more as priority pollutants needing increased regulation and long-term management (United States Environmental Protection Agency, 2023; World Health Organization, 2022).

With an increased understanding of the science of PFAS, regulators have begun moving beyond a substance-by-substance regulatory response to one of broader regulation in an effort to minimize exposure and protect human health. That said, international differences largely dictate the regulatory response, which in turn defines the environmental governance, the regulation of industry, and the affected economy.

1.2. Toxicological Evidence and Public Health Concerns

The last several decades have brought about an increased understanding of the health risks associated with PFAS exposure. Recently, studies have shown that PFAS exposure can result in toxicity and multiple system effects. These studies have shown effects such as disruption to the immune system, endocrine system, and liver. PFAS exposure can result in reproductive and developmental effects, thyroid disorders, a diminished response to vaccines, and an increased risk of certain cancers (Schiafone & Portesi, 2023).

A major health concern associated with PFAS is that they bioaccumulate. Unlike many traditional pollutants, they are not easily eliminated from the body. This causes them to persist in the bloodstream and other tissues for years. Consumers are continually exposed to PFAS in food, drinking water, and through consumer products. This means that there is a growing health burden that will have long-term effects on the public.

PFAS contamination has extended beyond effects on human health and become an environmental issue of its own. These persistent and mobile chemicals contaminate aquatic

environments, agricultural soils, and wildlife. They also invade and disrupt entire food chains at the expense of environmental and biological systems. PFAS persistence complicates and increases the expense of environmental remediation (Ahrens & Bundschuh, 2014; Xiao, 2017; Lindstrom *et al.*, 2011; Zareitalabad *et al.*, 2013; De Silva *et al.*, 2021).

As data continue to accumulate, researchers and advocates for policy change have begun to promote the regulation of PFAS as a chemical class. Unlike other chemical classes, the current regulation of PFAS as isolated chemicals has been particularly ineffective. Most PFAS share similar structures and behave in analogous ways to other chemical classes when they are released into the environment. Regulating the use of a select few PFAS allows industry to replace those PFAS with other PFAS of similar or the same structural class, severe, and comparable risk. This replacement practice has been called “regrettable substitution” and highlights a significant gap in PFAS governance (Kwiatkowski *et al.*, 2020; Blum *et al.*, 2015; Cousins *et al.*, 2020).

1.3. Regulatory Philosophies in the United States and Europe

Epidemiological studies coupled with toxicological studies have rapidly improved the understanding of PFAS over the last several decades. They have collectively demonstrated that the exposure of human beings to PFAS has systemic effects and diminished several biological systems. In particular, there are numerous documented effects on the human immune system, endocrine and hepatic systems, as well as reproductive and developmental health, and several thyroid disorders. Exposure to PFAS has also been shown to result in a diminished vaccine response and an increased risk of various cancers (Grandjean & Clapp, 2015).

PFAS raise numerous health concerns, largely attributed to their tendency to bioaccumulate. Compared to other traditional pollutants, PFAS have an unusual property of persistently remaining in human tissues and blood due to their slow rate of elimination. Thus, there is a cumulative increase of health risks to individuals exposed to PFAS through contaminated food and water or PFAS-laden consumer goods.

While there is an increase in evidence of PFAS harming human health, there is a growing body of literature on PFAS harming the environment. PFAS negatively impact ecosystems and bioaccumulate in the environment, freshwater, terrestrial, and marine ecosystems, and the food chain. PFAS persistence in the environment creates problems of increased complexity and cost of environmental remediation. (United Nations Environment Programme, 2023).

There is a clear increase in the evidence base, and researchers and policymakers are demanding immediate regulation to restrict PFAS as a class of chemicals. Due to the environmental behavior and chemical ecology of PFAS, regulation of only a few PFAS of concern invites the risk of replacing the restricted chemicals with similar, if not equivalent, PFAS. This is the practice of regrettable

substitution, and it is a major concern in PFAS regulation (Kwiatkowski *et al.*, 2020).

The structural diversity of PFAS, including fluoropolymers, perfluorinated non-polymers, polyfluorinated non-polymers, side-chain fluorinated polymers, and perfluoropolyether polymers, is illustrated in Figure 1.

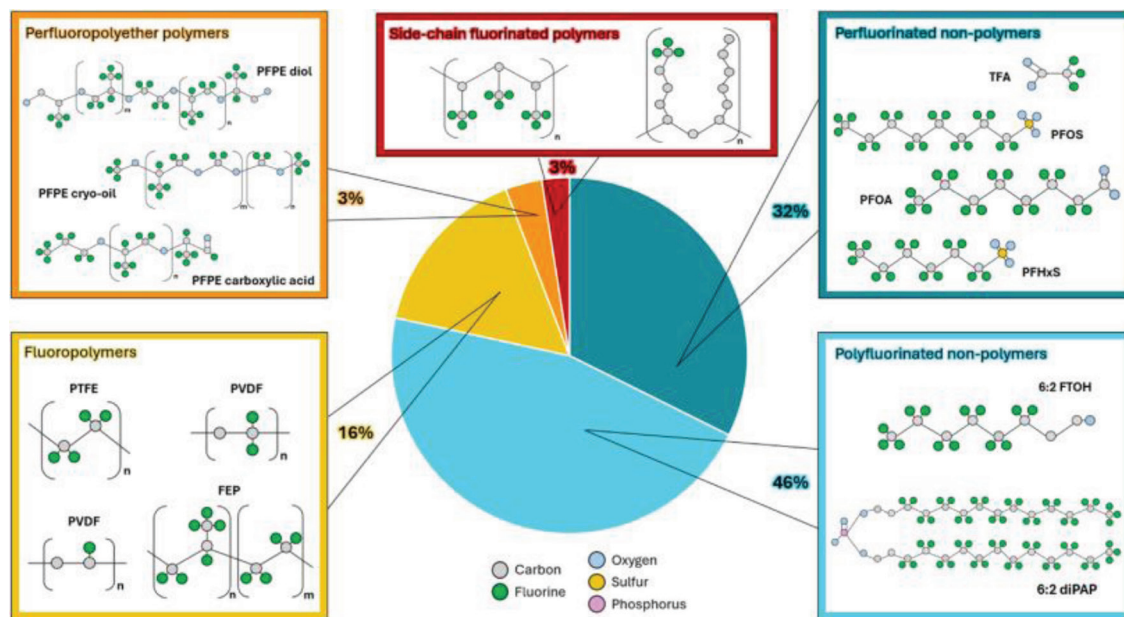


Figure 1: Major Structural Categories of Per- and Polyfluoroalkyl Substances and their Relative Representation

1.4. Industrial Dependence of the Food and Pharmaceutical Industries

Among the sectors impacted by PFAS regulations, the food and pharmaceutical industries have the most cause for concern. These sectors have a major reliance on industrial processes and manufacturing that incorporate PFAS. PFAS help create materials that are resistant to a variety of elements. However, their environmental and health concerns have prompted increasing regulatory control of their use.

In the food industry, PFAS have been incorporated into food packaging because of their waterproof and grease-resistant properties. PFAS can enter the food chain via contaminated soil and water, animal feed, or aquatic systems. In light of these concerns, food manufacturers are expected to strengthen their food safety monitoring and control systems, increase transparency in their supply chains, conduct testing and assessment, and use safer food packaging in order to be compliant with the law (Organisation for Economic Co-operation and Development, 2022; Torres & De-La-Torre, 2023; Souza & Domingo, 2025).

The challenges faced by the pharmaceutical industry are in many ways similar to those of the food industry but are more complicated. The manufacture of some pharmaceuticals requires the use of fluorinated compounds, which serve the same purposes as PFAS. For example, PFAS are used in a variety of manufacturing systems and materials. These include filtration systems, tubing, and seals as well as reactor linings and other specialized processing systems. Meeting safety and quality standards, as well as regulatory demands, are obstacles to replacing PFAS materials.

Consequently, PFAS-associated regulations result in higher operational costs due to the need to conduct research and development, change production processes, and validate products. The cost of securing new approvals from regulatory authorities also adds to operational costs and creates new challenges for companies that serve markets that are heavily regulated.

1.5. Economic Implications of PFAS Regulations

The introduction of PFAS regulations creates substantial new costs for many businesses, governments, and society.

Costs are incurred from the need to change business processes and focus on delivering new products, substitutes, and transportation, safety, and quality assurance. Smaller businesses are particularly affected due to limited finances and lack of technical resources.

The costs of these new regulations and the changes that are necessary to comply with the regulations are just one aspect of the overall negative impact. If new regulations are introduced that address PFAS contamination, the costs associated with cleaning up and restoring the environment, medical costs, and compensation costs that are the result of lawsuits will be much greater. Extensive PFAS contamination has clearly illustrated the costs associated with PFAS pollution that are incurred by businesses, governments, and local communities over many years.

In addition to the costs that will be incurred with compliance with PFAS regulations, the food industry will incur costs associated with product recalls. There will be costs associated with PFAS contamination, loss of trust and confidence by customers. The supply chain will also incur costs associated with restructuring. PFAS regulations will also result in increased costs for the pharmaceutical industry due to the replacement of equipment and regulatory approvals to repeal the validating of the manufacturing systems with the updated processes. The upfront costs associated with these measures are substantial, but the long-term benefit of liability and loss exposure cost reduction will be greater due to continued regulatory approvals for processes that are environmentally and socially sustainable.

Stricter PFAS regulations mean the chemical manufacturing industry has the incentive to design business models that reduce the overall burden of these regulations while also improving their bottom lines. These models may include innovations that replace harmful chemicals with safer alternatives, change the design of the manufacturing process to reduce waste and emissions, and/or produce sustainable design products. Ultimately, these innovations may make the industry as a whole more competitive.

1.6. Scope and Organization of the Review

This review examines PFAS regulations in the U.S. and the E.U. and their potential impacts on the food and pharmaceutical industries. It integrates academic publications and gray literature to document the interactions between industry, environmental protection, and the economy.

The first step in the review is establishing the science behind PFAS, their persistence in the environment, and the public health crisis they are creating. This is then contrasted with U.S. and E.U. regulations to differentiate PFAS market controls using a risk-based versus a precautionary approach.

The remaining sections of the review analyze the implications of PFAS regulations on the food and pharmaceutical industries in relation to the costs of compliance and the potential impacts: promotion of technological innovations, management of supply chain disruptions, increased litigation, and the costs of perpetual environmental damage. To further emphasize the implications of regulations on industry and society, case studies are included.

The review outlines the broader implications of the findings and suggests several areas for further investigation. The review calls for more robust international coordination of regulatory efforts, sustained investments in green industrial solutions, and improved methods for addressing the intersection of environmental and public health protection concerns. It hopes to better illustrate the nexus of PFAS regulation, advanced sustainable economic development, and the protection of ecological and public health concerns by combining science and policy analysis (Wang *et al.*, 2015).

2. Methodology

2.1. Research Design

This review takes a systematically analytical construct to PFAS regulations in the U.S. and the E.U. and their potential economic impacts on the food and pharmaceutical sectors. It employs a comparative and analytical methodology that draws from environmental science, public health, regulatory policy, and industrial economics. The review focuses on critical analysis of the literature in PFAS governance to identify the most pertinent similarities, differences, and newly emerging PFAS governance trends.

The comparative methodology provides an opportunity to analyze the implications of various regulatory schemes on a range of factors from compliance by industry to protection of public health, stimulation of innovation, and the attainability of sustainable economic development. Selected case studies illustrate the impacts of PFAS regulation on industry and public health.

2.2. Data Sources

The study is based on secondary data collected from reliable and authoritative sources. Data were derived from peer-reviewed articles, government reports, regulatory and policy documents, and scientific literature on the PFAS regulations and their economic impacts.

The US Environmental Protection Agency (U.S. EPA), European Chemicals Agency (ECHA), European

Food Safety Authority (EFSA), Organisation for Economic Co-operation and Development (OECD), and “numerous reputable international research databases (e.g., ScienceDirect, Scopus, Web of Science, PubMed, and Google Scholar) have been relied on as key resources for data and information.

To ensure the quality and reliability of the research, preference was given to more recently published research, professional regulatory documents, and internationally recognized peer-reviewed scientific journals. Additional information was obtained from published reviews by the relevant environmental organizations and international regulatory agencies.

2.3. Inclusion and Exclusion Criteria

Simple inclusion and exclusion criteria are customized to the installation to make sure of the appropriateness and relevance of the selected literature.

2.3.1. Inclusion Criteria

The review included:

- Peer-reviewed journal articles published between 2010 and 2026.

- Articles related to PFAS regulation, environmental management, toxicology, public health, and the economics of the case.
- Published position papers by the U.S. EPA, ECHA, EFSA, OECD, and other governmental agencies.
- Articles related to the food and drug manufacturing industries.
- Studies focused on the differences between the United States and European regulatory systems.

2.3.2. Exclusion Criteria

The following were excluded:

- Peer-reviewed articles that do not contain empirical research.
- Contents of journals, blogs, opinion pieces, or other non-academic websites.
- Articles that do not provide sufficient description of the methodology.
- Articles that do not contain references to PFAS regulation and the economic dimension of the case.
- Articles that are outdated and no longer relevant to the field, or articles that report the same research.

The selected literature was critically evaluated to ensure that it provides reliable evidence for the objectives of this research and for comparative analysis.

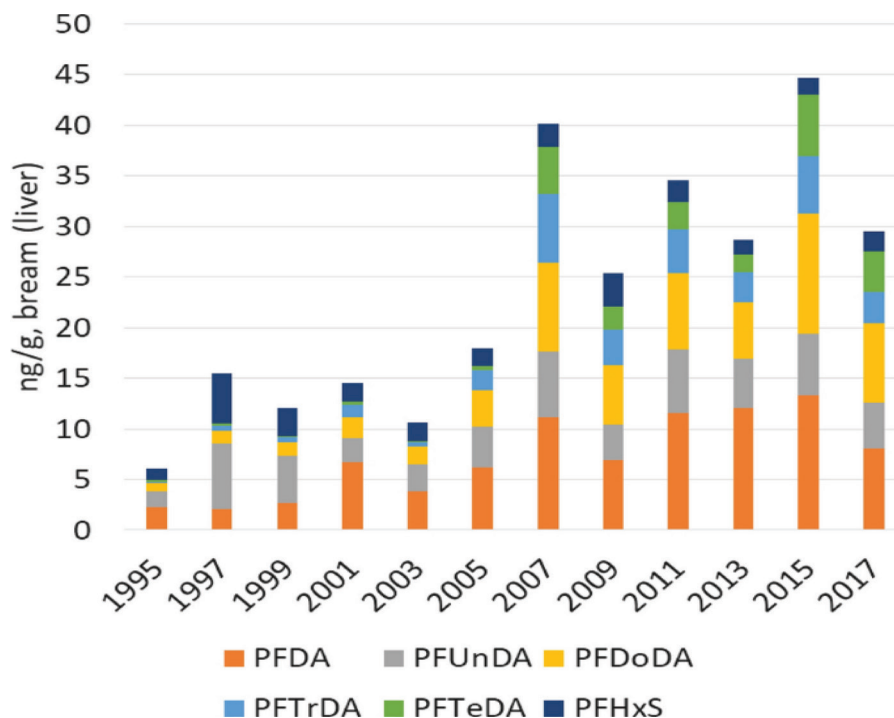


Figure 2: Temporal Concentrations of Selected Perfluoroalkyl Substances Measured in Liver Tissue

Note: PFDA: perfluorodecanoic acid; PFUnDA: perfluoroundecanoic acid; PFDODA: perfluorododecanoic acid; PFTTrDA: perfluorotridecanoic acid; PFTTeDA: perfluorotetradecanoic acid; and PFHxS: perfluorohexane sulfonate.

3. Institutional Divergence and Regulatory Paradigms in PFAS Governance

3.1. Conceptual Foundations of Environmental Regulatory Paradigms

The environmental regulation of Per- and Polyfluoroalkyl Substances (PFAS) primarily relies on two important regulatory frameworks: the hazard-based regulatory framework and the precautionary regulatory framework. The primary differences among the frameworks are in their understanding of the role of science, their approaches to managing uncertainty, and the timing of regulatory action. Consequently, they affect environmental governance, business compliance, public health, and the long-term sustainable economy (Jasanoff, 2005; Wiener *et al.*, 2011).

The risk-based regulatory framework is predicated on the availability of full scientific understanding and the assessment of risk prior to the implementation of regulation. With this framework, regulatory authorities are expected to evaluate the likelihood and the severity of adverse health and environmental impacts associated with individual PFAS compounds. Regulatory decisions are generally made only after sufficient scientific evidence illustrates that a chemical poses an unacceptable threat to human health or the environment (United States Environmental Protection Agency, 2024).

The precautionary regulatory framework, in contrast, permits a preventive regulatory action in the absence of full scientific understanding. Under the precautionary principle, regulatory authorities are compelled to act to protect the public if there is plausible evidence that a substance has the potential to cause serious or irreversible harm. This principle is particularly applicable to PFAS given their persistent nature, the potential to bioaccumulate, and their ubiquitous distribution in the environment (European Chemicals Agency, 2023).

These regulatory approaches have different implications for industrial development and environmental policies. The primary goal of the risk-based framework is the justification of economic growth at the expense of some environmental protection. The framework based on the precautionary principle seeks limiting potential environmental damage and risks to public health and, therefore, is oriented toward more protective and preventive strategies. This helps to illustrate the diverging paths of PFAS regulations within the U.S. and the European Union.

3.2. PFAS Regulation within the United States: A Risk-Based Regulatory Framework

The U.S. has mainly adopted the risk-based approach to the regulation of PFAS. U.S. PFAS regulation is grounded

in scientific studies that identify certain PFAS compounds as possessing risk. Federal regulatory initiatives have focused primarily on the more researched PFAS, such as perfluorooctanoic acid (PFOA) and perfluorooctane sulfonate (PFOS), among the many unregulated PFAS awaiting research (United States Environmental Protection Agency, 2024).

The U.S. Environmental Protection Agency (EPA) has some regulatory authority over PFAS among several federal environmental statutes that include the Safe Drinking Water Act (SDWA), the Toxic Substances Control Act (TSCA), and the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA). Key recent initiatives include the establishment of more stringent regulatory limits for PFAS in drinking water and a broader PFAS exposure mandate within the Agency's various fields of environmental oversight (United States Environmental Protection Agency, 2024).

U.S. PFAS regulations in recent years have continued to frustrate many. Regulatory concerns focus on PFAS use in the absence of full toxicological data, risk assessments, and formal evaluations of potential safety concerns. Unregulated PFAS use contributes to environmental damage, increased contamination, and increased human exposure. Remediation will also be more expensive (Cordner *et al.*, 2019).

The U.S. regulatory tool's decentralized governance model allows states to develop their own PFAS regulations. Many states have developed PFAS regulations that are more stringent than the federal regulations. While increased regulatory activity has created some level of inconsistency in the regulatory frameworks for industries that operate in multiple U.S. jurisdictions, it has been a positive development (Cordner *et al.*, 2019).

Litigation is an important tool to control PFAS use in the U.S. The lawsuits, in part, against major chemical companies, including 3M and DuPont, for the contamination of the water supply have resulted in settlements, valued in the billions, that require the companies to fund cleanup of the water supply and harm caused to the public (Cordner *et al.*, 2019; United States Environmental Protection Agency, 2024).

3.3. PFAS Regulation within the European Union: A Precautionary Regulatory Framework

The European Union (EU) has developed a precautionary regulatory framework for controlling PFAS that emphasizes avoiding creating environmental and public health threats over waiting to incur damage that can be considered irreversible. Unlike the United States, where regulatory lag is typical while waiting for sufficient scientific evidence to be developed, the European Union employs the precautionary

principle, which justifies early regulatory action during the presence of scientific uncertainty (European Chemicals Agency, 2023).

PFAS regulation within the European Union is generally accomplished through the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) Regulation. This regulation obliges manufacturers and importers to guarantee the safety of their chemicals prior to supplying them to the European market. Rather than the regulation of numerous individual PFAS compounds, the European Commission and ECHA increasingly endorse a class-based regulatory approach, given that many PFAS compounds share similar chemistry, environmental persistence, and toxicological problems (Kwiatkowski *et al.*, 2020; European Chemicals Agency, 2023).

The avoidance of “regrettable substitution” is a primary objective of the European regulatory framework. Regrettable substitution occurs when one restricted PFAS compound is replaced with several others that are environmentally and health concerning and are chemically similar. Therefore, the class-based regulation of PFAS is viewed as a more sustainable and effective long-term strategy for the control of these chemicals (Kwiatkowski *et al.*, 2020).

The European Food Safety Authority (EFSA) has made a significant contribution to strengthening PFAS legislation by establishing, for the first time, scientifically based, practically feasible, tolerable weekly intake (TWI) values for specific PFAS compounds. Their PFAS-related guidelines have resulted in the stricter testing of food products, drinking water, and environmental contamination across European Union member states (European Food Safety Authority, 2020).

While the precautionary principle may increase short-term compliance costs to industry, it may reduce long-term environmental remediation costs and promote the development of more environmentally friendly alternatives and innovations. For these reasons, the European Union is perceived as the global frontrunner in precautionary chemical legislation and environmentally sustainable governance (European Chemicals Agency, 2023).

3.4. Regulatory Divergence, Scientific Uncertainty, and Policy Implications

The differences in PFAS regulatory systems between the U.S. and the European Union encompass more than just legal frameworks and reveal significant differences in approaches to environmental governance and risk management. The effects of these differences are most clearly seen in the long-term economic consequences, as well as in the frameworks for corporate social responsibility and environmental governance.

In the U.S., scientific uncertainty is viewed as justification for a demand for further research prior to the introduction of regulatory measures. This approach aims to ensure that regulatory measures are fully grounded in the kind of scientific and economic research that is mobilized to support the measures. In the short term, this approach may avoid unnecessary regulatory burdens, but it may also eliminate safeguards for the environment and increase costs for future remediation (Jasanoff, 2005).

When clinically uncertain situations arise, the European Union takes preventive measures, and the precautionary principle is invoked. European Union regulatory authorities are likely to take measures to limit environmental or market risks. Graduate students and workers are more productive if the environment is safe, and so is the market (Wiener *et al.*, 2011).

While European companies face higher costs of doing business to be competitive internationally, such costs may be beneficial to the companies in the long term, as they are likely to avoid potential harm to their employees and long, costly, and drawn-out litigation.

In contrast, companies in the United States are not as cost burdened in the early stages of the formation of regulations. However, the lack of early regulations (that curtail probable future harm) may expose the employees and the company to future costly and lengthy litigation and damage to the company's reputation. Examples of this are the well-known cases of PFAS contamination from DuPont and 3M (Cordner *et al.*, 2019).

From the aforementioned, it is apparent that the European precautionary principle favors environmental protections, whereas in the United States, the principle of managing risk based on evidence is prevalent. Even though both of these approaches have their own advantages and disadvantages, from the standpoint of increasing international concern regarding PFAS, it is imperative that there be an improvement and an increase in the integration of international cooperation for the regulation of PFAS and in the alignment of international standards and policies in the field of science.

4. Industrial Consequences for the Food Industry

4.1. PFAS Exposure Pathways within the Food Industry

The food sector is a primary pathway for exposure to per- and polyfluoroalkyl substances (PFAS) for consumers. PFAS are incorporated into food packaging and other industrial applications due to their endurance against heat, grease, and moisture. Because of their persistent environmental

nature and ability to accumulate in living organisms, there is growing concern about the public and environmental impacts of these substances (Buck *et al.*, 2011; Sunderland *et al.*, 2019).

PFAS are capable of entering the food chain through a variety of environmental pathways. PFAS can accumulate in food, crops, and livestock through contaminated soil, irrigation water, and other water resources and even sewage sludge used in agriculture. Fish and shellfish are especially susceptible to the bioaccumulation of PFAS along aquatic food chains (Domingo & Nadal, 2017; Sunderland *et al.*, 2019).

Food contact materials are a significant route of exposure. Packaging that is used for fast food, microwave bags, bakery wrappers, and other disposable containers has been shown to contain PFAS. Research shows that PFAS migrate from food packaging into food when the packaging is exposed to high temperatures. Interestingly, PFAS can be present in the food consumed by the public, even when the food packaging was not contaminated (European Food Safety Authority, 2020).

As nutritional marketing is among the primary sources of human exposure to PFAS, food safety agencies globally have implemented stronger monitoring and established new protection requirements. Currently, regulatory agencies mandate the continuous monitoring of PFAS contamination of food products, drinking water, and food packaging to mitigate the risks to public health (European Food Safety Authority, 2020; European Chemicals Agency, 2023).

4.2. Operational Impact of PFAS Regulations on the Food Industry

Stricter PFAS regulations have significantly impacted the operations of food industry businesses. Food manufacturers are now required to meet more stringent regulations for both the environment and food safety. This has resulted in major overhauls in the food industry for the methods of production and safety, as well as for packaging and technology.

One of the most challenging regulatory issues has been to source alternatives to food packaging materials that are PFAS-containing. Because PFAS provide excellent protection from grease, moisture, and heat, it is a major challenge to identify alternative materials that would provide comparable performance in packaging. Because of this, companies have made greater use of research and development of more packaging materials to meet the requirements of environmental regulations while also ensuring food safety and quality (European Commission, 2020).

Food manufacturers are also required to implement more rigorous testing and monitoring programs for PFAS.

The more advanced analytical techniques, including LC-MS/MS, are being used more frequently for detection of PFAS at much lower levels in food and in the environment. Although this type of technology increases safety for consumers, it has a major impact on operating costs and regulatory compliance, especially for small and medium-sized businesses (European Food Safety Authority, 2020).

Additionally, PFAS tips show a need for greater transparency throughout the food supply chain. It's expected that companies will need to screen the raw materials, ensure their suppliers are compliant, maintain traceability records, and establish comprehensive systems to manage these risks. While these measures also improve safety and enhance customer confidence, they do require a considerable investment of time and money.

Incentivizing technological advancement, sustainable and improved manufacturing and environmental practices, and greater overall compliance are some of the long-term benefits to businesses of stricter PFAS controls. It is expected that there will be a long-term reduction in environmental contamination, a reduction in risks to the public's health, and an increase in consumer confidence with PFAS controls.

4.3. Economic Burden of PFAS Regulations in the Food Industry

The introduction of PFAS controls has financially strained the entire food sector. Changing environmental and food safety regulations requires significant investment in compliance controls that, on their own, drive up the cost of doing business, including product reformulation, regulatory-compliant packaging, environmental and food safety testing, and supply chain management. Stresses on the business are compounded by the need for continual adaptation to dynamic environmental and food safety regulations (European Food Safety Authority, 2020; European Chemicals Agency, 2023).

One of the major monetary concerns is the use of PFAS in food packaging. Because PFAS offer unique oil- and water-resistant abilities, it is technically difficult and expensive to identify potential substitute materials. Food manufacturers must undertake packaging alternatives' research and development, material selection, and regulatory approval (Kwiatkowski *et al.*, 2020).

A major economic concern is the cost and burden of environmental monitoring and assurance. Regulators now require testing of food, raw materials, water, and the places of food processing to determine "PFAS contamination. While the use of innovative evaluative methods like liquid chromatography-tandem mass spectrometry (LC-MS/MS) allows for better detection of PFAS, it drives up costs, particularly for small to medium businesses in the food sector (European Food Safety Authority, 2020).

PFAS contamination also introduces huge financial and legal concerns to food manufacturers. If contaminated food products reach the market, companies can incur costs and claims resulting from product recalls, compensation, regulatory actions, and damage to company reputation. These contribute to a decline in customer confidence and a disruption of the supply chain and affect the long-term viability of the business. Accordingly, companies have improved both their environmental risk management and business assurance practices to mitigate potential risks.

Although there are short-term monetary challenges associated with tightening PFAS standards, the long-term financial advantages from the increased environmental quality, reduced health care costs, increased consumer confidence, and reduced costs of cleaning up the environment will outweigh the costs of initial compliance. Thus, the investment in PFAS-free technologies and in the sustainability of the production process should be considered a long-term strategy for the enhancement of the firm's competitiveness and for the protection of public health.

4.4. Case Study: PFAS Contamination in Food Production – Belgium (3M Zwijndrecht)

A prime example of the financial consequences of PFAS contamination is located near the 3M plant in Zwijndrecht, Belgium. PFAS was found in local food products and in local transportation mediums such as ground and egg and vegetable packing. The Belgian government responded by limiting agricultural practices and recommended local consumers not to eat locally produced eggs and vegetables.

This caused a financial impact on farmers and local food producers as the consumer confidence drastically decreased, the market created a demand for a supply of safe food, and the production of contaminated food had to be stopped. Significant financial resources were also needed from government agencies to create safe food. This example illustrates that the delayed control of the PFAS contamination creates long-term financial impacts to the government and public health, which illustrates the need to create long-term policies and plans to mitigate PFAS contamination (European Chemicals Agency 2023, European Food Safety Authority 2020).

5. Consequences for the Pharmaceutical Sector

5.1. Role of PFAS in Pharmaceutical Manufacturing

PFAS are important in the pharmaceutical industry due to their exceptional stability, resistance to high temperatures, and

durability. While they are not the primary active pharmaceutical ingredients (APIs), PFAS and fluorinated compounds are widely used throughout the manufacturing process, including in laboratory equipment, filtration elements, reactor linings, seals, tubing, and specialized medical equipment. These substances improve the overall efficiency, quality, and reliability of the manufacturing processes under challenging conditions (Organisation for Economic Co-operation and Development, 2021; European Chemicals Agency, 2023).

As the pharmaceutical industry is governed by stringent quality and safety regulations set by country-specific and international regulatory bodies, the use of PFAS in manufacturing requires significant process validation and regulatory approval. There is increasing pressure on the pharmaceutical industry to find alternatives to PFAS to meet the growing demand for improved product quality, process efficiency, and safety of the end-user while maintaining the same quality and integrity of the manufacturing process (Organisation for Economic Co-operation and Development, 2021; European Chemicals Agency, 2023).

The increasing body of evidence on the persistence of PFAS and their harmful effects has encouraged the pharmaceutical industry to focus on the development of more sustainable and less harmful manufacturing processes. However, the challenges on the regulatory and technical front to replace PFAS with more sustainable alternatives that meet the same PFAS manufacturing process integrity and efficiency remain (Kwiatkowski *et al.*, 2020).

5.2 Regulatory Challenges and Industrial Adaptation

Stricter PFAS guidelines create significant regulatory and operational challenges for the pharmaceutical industry. Unlike many other business sectors, pharmaceutical manufacturers must comply not only with environmental regulations but also with critical regulations regarding the integrity of pharmaceuticals established by the Food and Drug Administration (2023), the European Medicines Agency (2023), and similar agencies. As such, the need to balance the requirements of regulatory compliance with the protections of the environment and the integrity of pharmaceutical manufacturing presents significant challenges.

One significant challenge is the removal of PFAS from manufacturing consumables and process aids. Any modification to established manufacturing processes requires extensive laboratory testing, the qualification of instrumentation, process validation, and regulatory approval prior to implementation. These requirements significantly increase the cost of compliance and may inhibit the adoption of newer manufacturing technologies (Food and

Drug Administration, 2023; European Medicines Agency, 2023).

Additionally, pharmaceutical companies must implement more comprehensive and stringent monitoring of the environment to ensure that the PFAS emitted by their manufacturing operations comply with the evolving environmental regulations. Real-time monitoring of the effluent, emissions, and wastes from the manufacturing operations has become a fundamental component of environmental risk management. These measures, while enhancing environmental protection, also require a significant investment in monitoring technologies, analytical instrumentation, and environmental management systems.

Pharmaceutical companies experiencing the effects of the stressful conditions are attempting to remedy the situations by utilizing green chemistry, sustainable production techniques, and PFAS-free options. The changes would help meet the regulations and improve the companies' environmental performance and public and self-esteem in regard to the manufacturing of pharmaceuticals. The changes are costly, but they are expected to improve the companies' sustainability and reduce the companies' environmental concerns and promote thoughtful economic growth in the future (Organisation for Economic Co-operation and Development, 2021; European Chemicals Agency, 2023).

5.3. Economic Impact of PFAS Regulations on the Pharmaceutical Industry

Stricter PFAS guidelines represent a sizeable financial burden to the pharmaceutical industry. The cost of maintaining PFAS regulations impacts the price of research and development, the cost of purchasing new machinery, the cost of environmental monitoring, and the cost of maintaining new regulations. Since the manufacturing of pharmaceuticals is highly regulated, the slightest change to the manufacturing process or the machinery has to be validated and approved, which increases the operational costs and the manufacturing time (Organisation for Economic Co-operation and Development, 2021; European Chemicals Agency, 2023).

The creation of PFAS manufacturing tools is one of the major financial challenges the industry is facing. The tools and the materials used to manufacture the tools need to be replaced with materials that have comparable chemical resistance and thermal stability. Such materials will have to be validated for use in the industry. The identification, testing, and validation of such alternatives have a significant financial investment and will negatively affect the productivity of the industry (Kwiatkowski *et al.*, 2020).

Pharmaceutical companies must also strengthen their systems for environmental monitoring and waste management, in addition to production changes. As governments implement new PFAS discharge regulations, companies must make greater investments in advanced wastewater treatment technologies, emissions control technologies, lab analysis, and environmental compliance. There are clear financial costs to these changes, but they also help reduce contamination and improve compliance with regulations (Organisation for Economic Co-operation and Development, 2021).

Managing the supply chain is also more complex. Pharmaceutical manufacturers need to ensure that their suppliers are screening for PFAS and are providing the necessary documentation for the chemicals with respect to their protection and their environmental performance. While audits, risk assessments, and the implementation of traceability systems are costly and require significant resources, they are necessary in order to maintain the quality of the product and the necessary regulatory compliance.

The innovation of clean technologies and processes provides a more positive and long-term outcome for the company. Even though the temporary costs of compliance with PFAS regulations are greater, the regulations provide an incentive for companies to invest in clean technologies and processes. These companies are expected to achieve a stronger long-term competitive position and lower their legal risks. Therefore, regulations for PFAS provide a financial incentive for companies to achieve commercial sustainability.

5.4. Case Study: 3M PFAS Manufacturing and Its Implications for the Pharmaceutical Supply Chain

3M's intent to isolate PFAS manufacturing to mitigate the risks associated with PFAS has brought into focus one of the most significant instances of the economic impact of PFAS legislation globally. 3M announced that due to increasing regulatory pressure, concerns regarding PFAS's impact on the environment, and the potential for increasing litigation, they will eliminate the manufacturing of PFAS and related products using PFAS and associated technologies by the end of 2025 (3M, 2022).

While the decision will most greatly affect the field of chemical manufacturing, the associated impacts will also be felt along the manufacturing supply chain, including the pharmaceutical industry. Several pharmaceutical companies relied on PFAS-based materials and technologies for specialized manufacturing, including filtration systems, seals, tubing, and desirable high-performance components for the consolidated daily activity packaging (CDAP). The discontinuation of PFAS manufacturing as a resource will

require manufacturers to focus on and source alternatives, qualify the new sources, modify manufacturing, and obtain the required regulatory approvals.

Changing over to the new materials will require substantial financial investments to be made in research, product testing, and the validation of manufacturing processes. During the change, resources will be reallocated to focus on the supply chain. As the change fosters innovation in the area of sustainable materials, it will benefit the pharmaceutical manufacturing industry and encourage the adoption of more environmentally sustainable manufacturing practices. From a regulatory perspective, this example illustrates the potential paradox of increased costs for businesses due to the introduction of new regulations for the PFAS legislation. However, business costs ultimately drive innovation in the field of environmental governance and sustainability with a positive impact on business sustainability (3M, 2022; Organisation for Economic Co-operation and Development, 2021; European Chemicals Agency, 2023).

6. Case-Based Evidence and Economic Consequences

6.1. Case Study 1: DuPont C8 Contamination, United States

One of the first and most studied PFAS contamination examples is the case of DuPont in Parkersburg, West Virginia. As part of its work with fluoropolymer products, DuPont used perfluorooctanoic acid (PFOA), also known as C8, during several manufacturing stages. Due to poor disposal methods, the nearby groundwater and surface water became fully contaminated, and hundreds of residents were exposed to PFAS through contaminated water (Sunderland *et al.* 2019). As a result, residents served as PFAS transporters to surrounding communities.

Epidemiological studies revealed PFOA exposure was associated with kidney and testicular cancer, thyroid disease and ulcerative colitis, and pregnancy-associated hypertension with elevated cholesterol, among various other negative health outcomes (Grandjean & Clapp, 2015). As a result of the new findings, stronger environmental protections were demanded.

There were also economic costs associated with this case, as DuPont lost billions due to legal costs, settlements, the required extensive environmental cleanup, and costs associated with claims and remediation. On top of the legal costs, government agencies assumed the costs associated with the absence of a fully defined environmental and health safety regulatory structure, as they were required to pour important resources into the investigations of environmental contamination and water safety (Cordner *et al.*, 2019).

Durable chemical case studies illustrate how poor oversight leads to all three: environmental, public, and economic health costs.

It also accelerated the development of more thorough PFAS regulations in the U.S. and Europe.

6.2. Case Study 2: European Union Restriction Proposal on PFAS

The European Union (EU) uses the REACH Regulation and the Precautionary Principle to manage PFAS contamination in the EU. PFAS Proposal 2023 was submitted by five EU countries—Germany, Denmark, the Netherlands, Norway, and Sweden—to the European Chemicals Agency (ECHA), proposing the first-ever regulation of PFAS as a unified class of chemicals in the manufacture, use, and marketing, as well as advertising and promotion (European Chemicals Agency, 2023).

Not only is this one of the most extensive chemical regulatory proposals in the world, but this proposal is built on the extensive challenges posed by PFAS as a class of chemicals. Instead of focusing on the regulation of individual PFAS compounds, the proposal targets the challenge of confusion associated with the regulation of the considerable PFAS compounds that have similar chemical structures, as well as their health risks and environmental mobility and persistence.

While the class-based regulation of PFAS will require significant investments in research and regulation, the anticipated benefits of the regulation include significant benefits in the public health and the environment, as well as the increased health and safety protection of the international markets. (Kwiatkowski *et al.*, 2020; European Chemicals Agency, 2023).

The European model illustrates that though precautionary environmental law may entail higher short-term compliance costs, it may also decrease long-term environmental and economic losses. As a result, the European Union increasingly enjoys the position of a world trailblazer in sustainable and precautionary environmental and chemical law.

6.3. Case Study 3: PFAS Contamination Around the 3M Facility, Zwijndrecht, Belgium

The PFAS contamination case around the 3M plant in Zwijndrecht, Belgium, is one of the most notable PFAS contamination cases in Europe. Environmental investigations observed a breakthrough in the concentration of PFAS in the solids, ground, and surface waters, and agricultural lands in the vicinity. Subsequent assessments of food safety discovered PFAS contamination in the local

agricultural produce, including eggs and vegetables. This raised considerable food safety and public health concerns (European Chemicals Agency, 2023; European Food Safety Authority, 2020).

In reaction to the findings, precautionary measures were introduced by the Belgian government, including recommendations to avoid the consumption of locally sourced food, enhanced environmental surveillance, and large-scale cleanup initiatives. There were significant socio-economic impacts, including a loss of business and a diminished and impacted food supply chain for farmers and food producers, a forced loss of confidence in the food market by consumers and food producers, mandatory testing of food products, declining food demand, adverse effects on public health and safety, and a loss of confidence in government regulatory controls.

PFAS case studies demonstrate contamination impacts that extend beyond the costs of cleaning the environment. The loss of agricultural productivity accompanies PFAS contamination, disruption to the food supply, lower profits, and higher costs for the public. The case also illustrates how regulators need to be more proactive and continuously assess the environment to avoid creating an unnecessary burden on the environment and economy (European Chemicals Agency, 2023).

6.4. Comparative Analysis and Policy Implications

The case studies reviewing PFAS contamination illustrate the large and negative environmental and economic impacts of PFAS contamination and the burden that it places on public health, regardless of location. However, the case studies illustrate the vast differences in public policy and regulation exhibited by the U.S. and the European Union, which are primarily driven by their differing philosophies of environmental protection and regulation.

The DuPont C8 contamination case illustrates the negative impacts of the public health and environmental demand for regulation within the context of a primarily risk-based regulatory framework. While the scientific demand for regulation resulted in litigation and the setting of regulation, the loss of public health and environmental protection caused widespread contamination and public demand for prolonged litigation (Cordner *et al.*, 2019; Sunderland *et al.*, 2019).

In comparison, the European Union's precautionary approach to regulation, including the setting of a PFAS limit in Belgium, illustrates the benefits of prevention on the protection of the environment. While industry costs and throughput diminished the benefits, the costs of the prevention burden on the environment, public health, and

litigation were reduced (Kwiatkowski *et al.*, 2020; European Chemicals Agency, 2023).

The food business measures the financial impacts of contaminated products through recalls, formulations, and supply chain management. The pharmaceutical business experiences challenges with production process validation, system changes, new approvals, and the use of PFAS-free technology. Despite the challenges these businesses face, all industries are beginning to invest in the use of sustainable manufacturing practices and less variable chemistry in response to changing regulatory demands.

The results of the analysis indicate that if PFAS were to be effectively governed, it would require more integrated global cooperation, regulatory harmonization, more investment in sciences, and greater innovations by industries. By creating balance through a precautionary approach to planning and evidence-based decision-making, a flexible regulatory system can strengthen the economy, improve public health, and enhance environmental protection. The analysis findings also indicate that creating regulations that proactively prevent PFAS contamination is more economically beneficial than trying to address the contamination aftermath.

7. Comparative Analysis of PFAS Regulatory Frameworks and Economic Implications

This section focuses on the regulatory frameworks of PFAS in the United States and the European Union (EU), with an emphasis on the frameworks' economic implications for the food and pharmaceutical industries. It identifies various "regulatory processes" and how they impact compliance by industries, protection of the environment, and sustainability in the long run. The analysis shows that both the United States and the EU strive to protect public health and the environment, but the two differ greatly in how they achieve these ends.

The United States tends to adopt a risk-based strategy for regulation, addressing specific PFAS compounds when the health or environmental risks are substantiated by a body of science. By contrast, the European Union adopts a precautionary strategy. This approach yields early intervention, despite the fact that scientific evidence is incomplete. The divergent approaches affect how businesses model, the costs of doing business, the state of the natural environment, and the economy over the long term.

The food sector is currently subjected to higher costs as a result of increasingly stricter regulation of packaging, contamination, testing, and management along the supply chain. The same is true of the pharmaceutical sector, which has made significant investments to change processes, monitor the environment, conduct validation studies, and

develop alternatives to PFAS. Although these measures are expensive to implement, they are expected to decrease future environmental obligations and enhance the sustainability of the commercial enterprise.

The comparative analysis also indicates that precautionary principles, while imposing greater short-term compliance costs, may yield longer-term benefits by avoiding liabilities associated with environmental cleanup, litigation, and health care. The case studies in the preceding section provide evidence for these claims.

Table 1: Comparative Analysis of PFAS Regulatory Frameworks in the United States and the European Union

Parameter	United States	European Union
Regulatory philosophy	Risk-based approach	Precautionary approach
Primary legislation	SDWA, TSCA, CERCLA	REACH Regulation
Regulatory focus	Individual PFAS compounds	PFAS as a chemical class
Decision-making	Evidence after risk assessment	Preventive action under scientific uncertainty
Regulatory implementation	Federal and state-level regulations	Harmonized EU-wide framework
Long-term goal	Risk management	Risk prevention and sustainability

Table 1 shows the main differences between the PFAS regulations of the US and the EU. It shows that currently the

US uses a risk-based regulatory approach, while the EU uses a precautionary approach under the REACH Regulation. The US approach is to regulate individual PFAS compounds after the exposure threshold is established. In contrast, the EU approach is to regulate PFAS as a class of compounds to support precautionary measures. The main implications of the differences between the two approaches are on industrial compliance, environmental protection, and the evolution of regulations.

Table 2: Economic Impact of PFAS Regulations on the Food and Pharmaceutical Industries

Economic Indicator	Food Industry	Pharmaceutical Industry
Product reformulation	High	Moderate
Packaging modification	Very High	Low
Manufacturing process changes	Moderate	Very High
Laboratory testing	High	High
Environmental monitoring	High	High
Compliance cost	High	Very High
Supply chain adjustment	High	Moderate
Long-term sustainability benefits	High	High

The sector-specific economic implications of PFAS regulations for the food and pharmaceutical industries are summarized in Table 2.

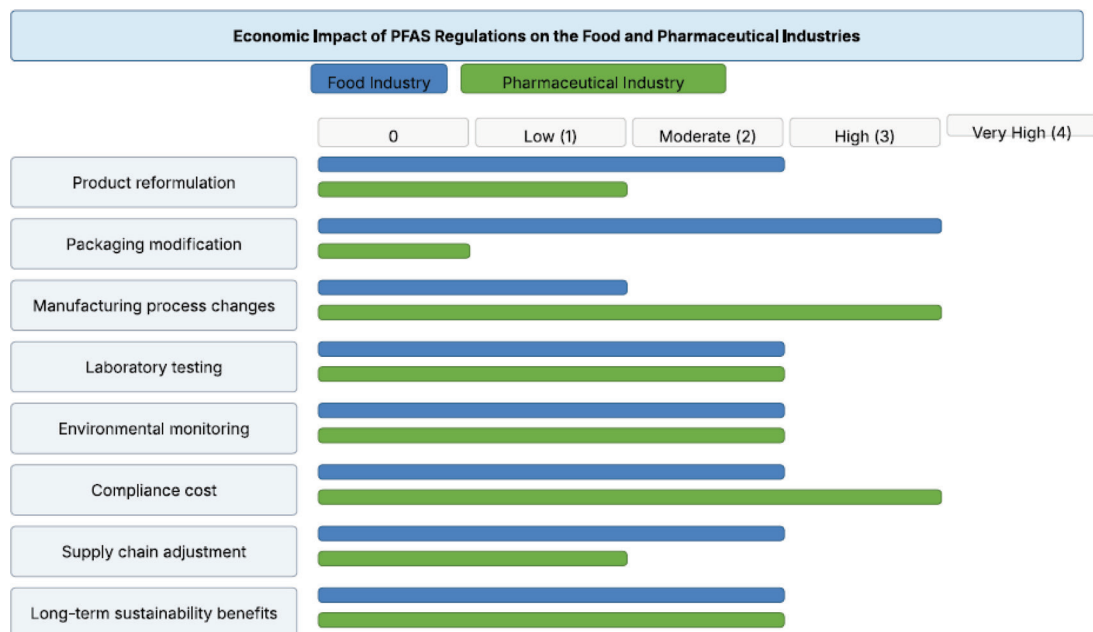


Figure 3: Comparative Economic Impacts of PFAS Regulations on the Food and Pharmaceutical Industries

The qualitative ratings correspond to the indicators summarized in Table 2. Table 7.2 shows how the food and pharmaceutical industries are impacted economically by PFAS regulations. There are new cost implications and greater regulatory burdens in both industries, but they are especially the focus of different implications. The food industry primarily has implications in the reformulation of packaging, supply chain management, and contamination testing. Meanwhile, the pharmaceutical industry primarily has cost implications in process validation, equipment, and new approvals. The financial burden is significant, but both industries expect improvement in environmental performance, a reduction in the risk of litigation, and an increase in consumer trust.

Table 3: Comparative Advantages and Challenges of PFAS Regulatory Approaches

Aspect	United States	European Union
Initial compliance cost	Lower	Higher
Regulatory flexibility	High	Moderate
Environmental protection	Moderate	Very High
Litigation risk	High	Low
Innovation in safer alternatives	Moderate	High
Long-term remediation cost	High	Lower
Public health protection	Moderate	Very High
Overall sustainability	Moderate	High

Table 3 shows summary of the strengths and weaknesses of PFAS-related regulatory approaches in the U.S. and the EU. With respect to PFAS regulation, the U.S. system's regulatory flexibility and lower compliance cost motivate short-term adoption but may lead to long-term remediation and litigation costs. On the other hand, the EU system's precautionary principle may lead to high upfront costs but offers stronger environmental protection, better health outcomes, and more sustainable economies. Within this context, the preventive regulation of PFAS in the U.S. and EU systems appears to be more effective in minimizing future environmental and economic costs.

The comparative analysis shows that distinct advantages and disadvantages characterize both systems. The U.S. system allows more regulatory flexibility, particularly in the early stages of PFAS regulation, but at the expense of increased long-term environmental and legal costs. On the contrary, the EU system's precautionary principle ensures a high level of environmental, health, and economic quality at the cost of a high level of upfront investment. The findings of this analysis support the rationale for international regulatory collaboration and alignment of scientific standards, along

with the continued support for the development of safer alternatives to effectively regulate PFAS.

8. Discussion, Conclusion, and Future Directions

8.1. Discussion

The results indicate that the regulation of PFAS has emerged at the intersection of environmental governance and industrial sustainability. The U.S. and EU systems, although both aim to enhance the protection of human health and the environment, differ substantially in the style and procedure of regulation, as well as in economic burden.

The United States mainly uses a risk-based regulatory system. Here, a response to a particular PFAS compound is only triggered when risk is proven through science. The European Union, however, uses a precaution-based system. They are more likely to respond to the potential risk, even if science has not confirmed the risk. This type of distinction is likely to impact the compliance of industry, the actualization of innovations, and the preservation of environmental concerns, as well as the sustainability of the economy in the long run (Jasanoff, 2005; Wiener *et al.*, 2011).

The review identifies the distinct challenges PFAS regulation poses to the food and pharmaceutical sectors. There are increasingly more challenges for the food sector from monitoring PFAS contamination, reformulating food contact materials, testing, and managing the PFAS supply chain. For the pharmaceutical sector, the emerging PFAS regulations impose considerable new costs for the validation of new processes and accompanying new equipment and regulatory approval for the use of new substituted materials. Nevertheless, both sectors are making significant investments to develop more sustainable manufacturing processes.

The case studies in the review clearly demonstrate the negative consequences of the failure to regulate emerging contaminants. There were environmental pollution, loss of public trust, large financial costs, and legal challenges. The well-known cases of DuPont in the USA and 3M in Belgium demonstrate that for the regulatory authority, the costs of prevention are substantially lower than the long-term costs of litigation and the restoration of the polluted environment. This supports a pre-emptive approach to regulation.

8.2. Conclusion

Omnipresence of per- and polyfluoroalkyl substances (PFAS) poses environmental, public health, and economic challenges due to their persistence, extensive use, and resistance to environmental breakdown. This review focuses

on regulatory frameworks relevant to the U.S. geographic region and the European Union and assesses their economic impacts on the food and pharmaceutical sectors.

The analysis shows that the European Union's precautionary approach provides an improved public health and environmental safety framework through early-stage regulatory interventions and the planned grouping-based control of PFAS. In comparison, the U.S. approach is mostly based on managing risk, allowing greater flexibility to the industry, but may increase the long-term costs of environmental remediation and legal issues.

Emerging stricter PFAS regulations will require significant investment in compliance, industrial, and technological changes. However, these changes will bring positive environmental and public health and sustainable economic development. Thus, the adoption of innovative, transparent, and internationally harmonized Type I regulations will help address the challenges of PFAS while supporting economic development and enterprise competitiveness.

8.3. Future Directions

Future studies should create safer, more sustainable alternatives to PFAS used in the food and pharmaceutical sectors. Additionally, more focus should fall on the development of advanced manufacturing technologies coupled with green chemistry that will reduce reliance on harmful persistent chemistries.

Governments, regulators, researchers, and industry stakeholders need to work together to develop PFAS-related regulations. Aligning PFAS regulations, risk assessment, and monitoring methodologies will foster a consistent and flexible approach to international trade and enhance environmental protection.

Socio-economic impacts of PFAS regulation should take into account an assessment of the socio-economic costs of healthcare and environmental remediation, the cost of lost competitiveness, and the cost of changing patterns of consumption. Funding research on new types of PFAS, cutting-edge detection technologies, and innovative remediation techniques will also create the groundwork for effective policy.

Flexible precautionary approaches to regulation, combined with scientific evidence and sustainable technologies and practices, will support long-term economic stability and environmental protection.

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Human and Animal Right Statement

This article does not contain any studies involving human participants or animals performed by any of the authors.

Conflict of Interest

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References

- 3M. (2022). *3M to exit PFAS manufacturing by the end of 2025*. <https://www.3m.com/>
- Ahrens, L., & Bundschuh, M. (2014). Fate and effects of poly- and perfluoroalkyl substances in the aquatic environment: A review. *Environmental Toxicology and Chemistry*, 33(9), 1921–1929. <https://doi.org/10.1002/etc.2663>
- Blum, A., Balan, S. A., Scheringer, M., Trier, X., Goldenman, G., Cousins, I. T., Diamond, M., Fletcher, T., Higgins, C., Lindeman, A. E., Peaslee, G., de Voogt, P., Wang, Z., & Weber, R. (2015). The Madrid Statement on poly- and perfluoroalkyl substances (PFASs). *Environmental Health Perspectives*, 123(5), A107–A111. <https://doi.org/10.1289/ehp.1509934>
- Buck, R. C., Franklin, J., Berger, U., Conder, J. M., Cousins, I. T., de Voogt, P., Jensen, A. A., Kannan, K., Mabury, S. A., & van Leeuwen, S. P. J. (2011). Perfluoroalkyl and polyfluoroalkyl substances in the environment: Terminology, classification, and origins. *Integrated Environmental Assessment and Management*, 7(4), 513–541. <https://doi.org/10.1002/ieam.258>
- Cordner, A., De La Rosa, V. Y., Schaidler, L. A., Rudel, R. A., Richter, L., & Brown, P. (2019). Guideline levels for PFOA and PFOS in drinking water: The role of scientific uncertainty, risk assessment decisions, and social factors. *Journal of Exposure Science & Environmental Epidemiology*, 29(2), 157–171. <https://doi.org/10.1038/jes.2018.115>
- Cousins, I. T., DeWitt, J. C., Glüge, J., Goldenman, G., Herzke, D., Lohmann, R., Ng, C. A., Scheringer, M., & Wang, Z. (2020). The high persistence of PFAS is sufficient for their management as a chemical class. *Environmental Science: Processes & Impacts*, 22(12), 2307–2312. <https://doi.org/10.1039/D0EM00355G>
- De Silva, A. O., Armitage, J. M., Bruton, T. A., Dassuncao, C., Heiger-Bernays, W., Hu, X. C., Kärrman, A., Kelly, B., Ng, C., Robuck, A., Sun, M., Trier, X., Wang, Z., & Sunderland, E. M. (2021). PFAS exposure pathways for humans and wildlife: A synthesis of current knowledge and key gaps. *Environmental Toxicology and Chemistry*, 40(3), 631–657. <https://doi.org/10.1002/etc.4935>
- Domingo, J. L., & Nadal, M. (2017). Per- and polyfluoroalkyl substances (PFASs) in food and human dietary intake: A review of the recent scientific literature. *Journal of Agricultural and Food Chemistry*, 65(3), 533–543. <https://doi.org/10.1021/acs.jafc.6b04697>
- European Chemicals Agency. (2023). *Proposal for a restriction on per- and polyfluoroalkyl substances (PFASs) under REACH*. Helsinki, Finland: European Chemicals Agency. <https://www.echa.europa.eu/web/guest/-/restriction-of-per-and-polyfluoroalkyl-substances-pfass-under-reach>
- European Commission. (2020). *Chemicals Strategy for Sustainability: Towards a Toxic-Free Environment*. Brussels, Belgium: European Commission. <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0667>
- European Food Safety Authority (EFSA). (2020). Risk to human health related to the presence of perfluoroalkyl substances in food. *EFSA Journal*, 18(9), e06223. <https://doi.org/10.2903/j.efsa.2020.6223>
- European Medicines Agency. (2023). *Environmental risk assessment of medicinal products for human use*. Amsterdam: European Medicines Agency. <https://www.ema.europa.eu/en/environmental-risk-assessment-medicinal-products-human-use-scientific-guideline>
- Food and Drug Administration. (2023). *Guidance for industry: Environmental assessment of human drug and biologics applications*. Silver Spring, MD: U.S. Food and Drug Administration. <https://www.fda.gov/regulatory-information/search-fda-guidance-documents/environmental-assessment-human-drug-and-biologics-applications>
- Grandjean, P., & Clapp, R. (2015). Perfluorinated alkyl substances: Emerging insights into health risks. *New Solutions: A Journal of Environmental and Occupational Health Policy*, 25(2), 147–163. <https://doi.org/10.1177/1048291115590506>
- Jasanoff, S. (2005). *Designs on nature: Science and democracy in Europe and the United States*. Princeton University Press. <https://search.worldcat.org/title/880744367>
- Kwiatkowski, C. F., Andrews, D. Q., Birnbaum, L. S., Bruton, T. A., DeWitt, J. C., Knappe, D. R. U., Maffini, M. V., Miller, M. F., Pelch, K. E., Reade, A., Soehl, A., Trier, X., Venier, M., Wagner, C. C., Wang, Z., & Blum, A. (2020). Scientific basis for managing PFAS as a chemical class. *Environmental Science & Technology Letters*, 7(8), 532–543. <https://doi.org/10.1021/acs.estlett.0c00255>
- Lindstrom, A. B., Strynar, M. J., & Libelo, E. L. (2011). Polyfluorinated compounds: Past, present, and future. *Environmental Science & Technology*, 45(19), 7954–7961. <https://doi.org/10.1021/es2011622>
- Organisation for Economic Co-operation and Development (OECD). (2021). *Reconciling terminology of the universe*

- of per- and polyfluoroalkyl substances (PFASs): Revised recommendations and practical guidance. Paris: OECD Publishing. https://www.oecd.org/en/publications/reconciling-terminology-of-the-universe-of-per-and-polyfluoroalkyl-substances_e458e796-en.html
- Organisation for Economic Co-operation and Development. (2022). *PFASs and alternatives in food packaging (Paper Series on Risk Management No. 68)*. Paris: OECD Publishing. <https://www.oecd.org/chemicalsafety/risk-management/pfass-and-alternatives-in-food-packaging.htm>
- Schiavone, C., & Portesi, C. (2023). PFAS: A review of the state of the art, from legislation to analytical approaches and toxicological aspects for assessing contamination in food and environment and related risks. *Applied Sciences*, 13(11), 6696. <https://doi.org/10.3390/app13116696>
- Souza, M. C. O., & Domingo, J. L. (2025). Levels of per- and polyfluoroalkyl substances (PFAS) in foodstuffs: A review of dietary exposure, health risks, and regulatory challenges. *Food Research International*, 221, 117494. <https://doi.org/10.1016/j.foodres.2025.117494>
- Sunderland, E. M., Hu, X. C., Dassuncao, C., Tokranov, A. K., Wagner, C., & Allen, J. G. (2019). A review of the pathways of human exposure to poly- and perfluoroalkyl substances (PFASs) and present understanding of health effects. *Journal of Exposure Science & Environmental Epidemiology*, 29(2), 131–147. <https://doi.org/10.1038/s41370-018-0094-1>
- Torres, F. G., & De-La-Torre, G. E. (2023). Per- and polyfluoroalkyl substances (PFASs) in consumable species and food products. *Journal of Food Science and Technology*, 60(9), 2319–2336. <https://pubmed.ncbi.nlm.nih.gov/37424586/>
- United Nations Environment Programme. (2023). *Global chemicals outlook II: From legacies to innovative solutions*. Nairobi: UNEP. <https://wedocs.unep.org/handle/20.500.11822/28113>
- United States Environmental Protection Agency. (2024). *National primary drinking water regulation for PFAS*. Washington, DC: U.S. EPA. <https://www.epa.gov/sdwa/and-polyfluoroalkyl-substances-pfas>
- United States Environmental Protection Agency. (2024). *PFAS Strategic Roadmap: EPA's commitments to action 2021–2024*. Washington, DC: U.S. Environmental Protection Agency. https://www.epa.gov/system/files/documents/2021-10/pfas-roadmap_final-508.pdf
- Wang, Z., Cousins, I. T., Scheringer, M., & Hungerbühler, K. (2015). Hazard assessment of fluorinated alternatives to long-chain perfluoroalkyl acids (PFAAs). *Environment International*, 75, 172–179. <https://doi.org/10.1016/j.envint.2014.11.010>
- Wang, Z., DeWitt, J. C., Higgins, C. P., & Cousins, I. T. (2017). A never-ending story of per- and polyfluoroalkyl substances (PFASs)? *Environmental Science & Technology*, 51(5), 2508–2518. <https://doi.org/10.3390/app13116696>
- Wiener, J. B., Rogers, M. D., Hammitt, J. K., & Sand, P. H. (Eds.). (2011). *The reality of precaution: Comparing risk regulation in the United States and Europe*. Routledge. <https://doi.org/10.4324/9781936331802>
- World Health Organization (WHO). (2022). *PFAS in drinking water: Background document for development of WHO Guidelines for Drinking-water Quality*. Geneva: WHO. <https://apps.who.int/iris/bitstream/handle/10665/352545/9789240044558-eng.pdf>
- Xiao, F. (2017). Emerging poly- and perfluoroalkyl substances in the aquatic environment: A review of current literature. *Water Research*, 124, 482–495. <https://doi.org/10.1016/j.watres.2017.06.061>
- Zareitalabad, P., Siemens, J., Hamer, M., & Amelung, W. (2013). Perfluorooctanoic acid (PFOA) and perfluorooctanesulfonic acid (PFOS) in the environment: A review of their occurrence and fate. *Journal of Environmental Quality*, 42(6), 1807–1821. <https://doi.org/10.2134/jeq2012.0536>