Analyzing the Barriers of Transitioning to PFAS-Free Alternatives in the Food Packaging Industry

Applying the Technological Innovation Systems framework to Analyze the Transition to PFAS-Free Alternatives in the Food Packaging Industry

Assignment SEN2331

Jos Groendijk

Student Number: 5645050

Graduation committee:

Chairperson: Dr. J.A. Annema
First Supervisor: Dr.ir. B.F.H.J. Bouchaut
Second Supervisor: Dr. ir. O.E. Popa
Daily Supervisor: Msc. D. Perfigli

CoSEM Master Thesis

MSc Complex Systems Engineering and Management

Delft University of Technology

December 17, 2024

Acknowledgement

Writing this thesis has been one of the most challenging yet rewarding experiences of my life. The journey was marked by tough moments and challenging circumstances, but it has also been a period of immense personal and academic growth. I have learned lessons that extend far beyond the scope of this research, and this chapter of my life is one I will never forget.

First and foremost, I would like to express my deepest gratitude to my graduation committee: Jan Anne Annema, Britte Bouchaut, Eugen Popa, and Dario Perfigli. Each of you brought unique expertise and perspective, complementing one another to form an incredibly supportive yet critical supervisory team. Your guidance, constructive feedback, and unwavering support have been instrumental in helping me complete this work.

On a personal level, I owe endless thanks to my family. To my mother, father, sister, and Phil, your unwavering love and encouragement carried me through the most difficult times. Your support has been my rock, and I cannot express how much it has meant to me.

I am also incredibly grateful to my friends and roommates for their mental support throughout this process. During tough moments, you were always there to cheer me up, lift my spirits, and remind me to smile and laugh. You helped me push through, and I will always cherish the memories we created along the way.

Finally, a very special thank you goes to my best friend, Maxim Houwink. Your support has been immense, particularly during our long study sessions. You stood by me every step of the way, motivating me to persevere and work toward this final result. I could not have done it without you.

Abstract

Problem introduction Per- and polyfluoroalkyl substances (PFAS) have been extensively used in the food packaging industry due to their exceptional water and oil repellency, providing essential barrier protection for products like pizza boxes, fast-food containers, and microwave popcorn bags. However, PFAS are highly persistent in the environment and have been linked to significant health risks, including bioaccumulation in humans and wildlife. The widespread contamination and toxicity concerns have prompted regulatory actions, notably the European Union's (EU) proposed comprehensive ban on PFAS. Despite this regulatory pressure, transitioning to PFAS-free alternatives in the food packaging and food contact materials industry presents complex challenges.

Research objective and main research question

The objective of this study is to identify and analyze the key technical, regulatory, economic, and social barriers hindering the adoption of PFAS-free alternatives in the food packaging industry.

The main research question guiding this thesis is:

What are the key challenges for implementing PFAS-free alternatives in the food packaging & food contact materials industry?

Methods To address this, the research applies the Technological Innovation Systems (TIS) framework, which analyzes the dynamics of innovation processes and the roles of various actors, networks, and institutions. Data collection involved a comprehensive literature review, analysis of scientific reports, examination of the annex of the European Chemicals Agency's (ECHA) PFAS ban proposal, semi-structured interviews with key stakeholders (including manufacturers, regulators, NGOs, and industry representatives), and analysis of stakeholder responses during the ECHA's public consultation process. Qualitative content analysis and thematic coding were employed to interpret the data and identify systemic problems within the TIS.

Results The results highlight systemic barriers across multiple dimensions: manufacturers exhibit a lack of entrepreneurial activity and struggle to effectively utilize available knowledge and resources, while institutional challenges such as the absence of clear incentives, fragmented regulations, and regulatory ambiguities further hinder the transition. Additionally, weak coordination and mismatched priorities among stakeholders exacerbate the difficulty of creating alignment and legitimacy for PFAS-free alternatives. The study emphasizes that these barriers can be effectively addressed through the implementation of the comprehensive PFAS ban combined with collaborative efforts from key stakeholders. Strategies such as financial and technical support for innovation, harmonization of EU-wide regulations, and the creation of platforms for knowledge sharing and stakeholder alignment offer realistic and feasible pathways to guide the industry toward PFAS-free alternatives. These measures not only address the systemic problems but also build a foundation for sustainable innovation and market formation.

Discussion This study contributes new knowledge by providing critical insights into the implementation of the proposed PFAS ban and its practical implications. The discussion highlights the positive relevance of the findings, as the results suggest that nearly all identified systemic barriers can be overcome through targeted regulatory measures and stakeholder collaboration. The practical relevance of this research is underscored by its demonstration that the current obstacles are surmountable with realistic interventions, offering actionable recommendations for the food packaging industry to transition toward PFAS-free solutions. **Future research** Future research should focus on evaluating the long-term performance and socio-economic impacts of alternatives while exploring mechanisms to scale their adoption across the industry.

Contents

List of Figures

List of Tables

PFAS Per- and polyfluoroalkyl substances

EU European Union

REACH Registration, Evaluation, Authorisation and Restriction of Chemicals

TIS Technological Innovation Systems

CF3 trifluoromethyl

CF2 difluoromethylene

ECHA European Chemicals Agency

OECD Organisation for Economic Cooperation and Development

PLC Polymers of Low Concern

NGO Non-Governmental Organisation

1 Problem Analysis

Per- and polyfluoroalkyl substances (PFAS) are a vast group of synthetic chemicals that have been widely utilized in various industrial processes and consumer goods since the early 1950s (Prevedouros et al., 2006). These substances are highly resistant to heat, water, and oil, and are renowned for their stability and persistence in the environment (Gï et al., 2020). The robust nature of PFAS makes them extremely popular in diverse industrial and consumer applications, such as oil and water repellents, firefighting foams, chemical manufacturing, food packaging, and cosmetics (Gï et al., 2020).

The widespread use of PFAS has raised concerns due to the toxicity and long-term persistence of certain compounds within this class, both environmentally and biologically (Gï et al., 2020). PFAS encompass a diverse class of chemicals with varying functionalities and characteristics, including their unique resistance to heat, water, oil, and chemical degradation. (Schiavone and Portesi, 2023). The most commonly detected and studied PFAS are essentially non-degradable (Reinikainen et al., 2024), thereby persisting in the environment and accumulating in the human body, which leads to severe health risks over time (Gï et al., 2020). However, not all PFAS exhibit the same level of toxicity or persistence, highlighting the complexity and variability of these substances. The PFAS contamination is spreading across Europe, originating from the major PFAS polluters, such as chemical manufacturing facilities, industrial sites producing PFAS-containing products, and waste disposal or incineration plants where PFAS are not effectively contained (see figure 1) (ECHA, 2023).

This complex situation has prompted five European Union (EU) Member States (Germany, the Netherlands, Denmark, Sweden, and Norway) to propose a complete ban on PFAS, highlighting the ongoing debate between their indispensable industrial uses and the environmental and health risks they pose (ECHA, 2023). In this proposal of a PFAS-ban, the EU proposal does not differentiate among PFAS variations, despite their chemical diversity with varying toxicity levels, potentially hindering industries relying on safer PFAS with minimal environmental and human impact, while diverting focus from more harmful compounds. (Wang et al., 2021).

Despite these concerns, PFAS are valued for their specific advantageous properties, such as their high resistance to heat, water, and chemicals, which make them essential in various applications within the healthcare sector (e.g., medical equipment coatings and protective gear) and the energy sector (e.g., use in renewable energy technologies and batteries)(Spyrakis and Dragani, 2023).

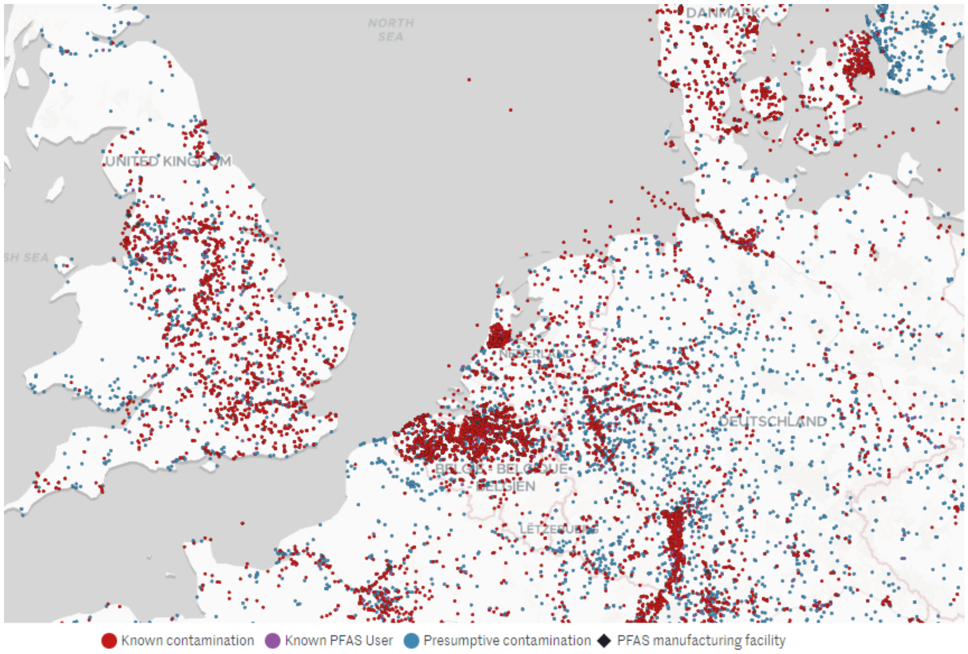

Figure 1: Map of Europe's PFAS contamination by ECHA (2023)

For material chemists, finding an alternative to PFAS that replicates its unique combination of properties, such as thermal stability, water repellence, and chemical resistance poses significant challenges. This difficulty stems from the limited availability of materials that can achieve the same functional performance as some PFAS. As a result, the transition to sustainable energy may face delays, as current research has yet to produce adequate substitutes that meet the demanding specifications required for such applications (Spyrakis and Dragani, 2023).

The EU proposal categorizes PFAS use across industries into three distinct groups: non-essential, substitutable, and essential use (Cousins et al., 2019). A complete ban applies to industries designated as non-essential users of PFAS, as well as most substitutable users. However, for industries deemed essential users of PFAS, time-limited exemptions are provided to facilitate their transition, which can differ from a derogation time of 5 years till 12 years (ECHA, 2023).

The current lack of innovation in PFAS alternatives leaves a significant gap in various applications, especially in applications that require high-performance attributes, such as firefighting foams requiring high thermal stability and rapid spreading capabilities, semiconductor manufacturing that needs extreme chemical resistance, enhanced oil recovery processes that benefit from surface tension reduction, and food contact materials that rely on oil and water repellence (Steindal and Grung, 2021). This process is hindered by technical challenges of finding comparable functioning alternatives, market resistance of the industry, regulatory pressure, and a lack of comprehensive toxicological data for many PFAS compounds (Wang et al., 2021, Spyrakis and Dragani, 2023).

The high degree of interdependence between technical advancements and the regulatory and policy structures that govern their implementation necessitates a coordinated, multi-disciplinary approach to identify and address the barriers hindering the adoption of PFAS alternatives. Targeted EU policies can facilitate stakeholder coordination and collaboration, bringing together government agencies, industry players, researchers, and environmental groups to share knowledge and resources.

1.1 Scope

In this thesis project, the food packaging and contact materials industries are investigated, including products such as pizza boxes, food wrapping materials, microwave popcorn bags, fast food containers, and paper plates. These products require water and oil resistance, making PFAS an ideal additive due to its barrier protection (Glenn et al., 2021).

This industry presents an interesting and challenging case for analysis in this thesis, because it encompasses two distinct categories of products: those for which PFAS-free substitutes are already available, and those for which such substitutes either do not yet exist or are still in the early stages of development. The dual nature of this challenge makes the food packaging sector particularly significant in the context of the upcoming PFAS regulations.

The proposal for the PFAS restriction, requested through an EU Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) procedure by the European Chemicals Agency (ECHA), was submitted on 13 January 2023 (ECHA, 2023). The ECHA, which is responsible for implementing chemical regulations within the EU, facilitates the REACH procedure to evaluate and control chemicals that pose potential risks. If adopted, the regulation would include an 18-month transition period before the restriction is fully enforced. At that point, products are not longer permitted to contain PFAS concentrations above a specified limit. Given that people are in direct contact with food packaging and food contact materials, the urgency for a rapid transition to PFAS-free alternatives in this industry is paramount. The upcoming PFAS ban increases the urgency, making it crucial to quickly find and implement safe alternatives before the ban is fully enforced.

1.2 Knowledge Gap

Since the dentrimental effects on the public health and environment of most PFAS is clear, non-degradable and spreading quickly through waters, targeted policy is required to accelerate the development and adoption of difficult-to-replace alternatives to PFAS (Cousins et al., 2019). The non-essential use of PFAS can be phased out via regulation. However, in the areas of fluoropolymer production, oil recovery, the semiconductor industry, and the food packaging & food contact materials industry, the situation is more complex. Because of the demanding and highly diverse conditions or the many interlinked processes with many different PFAS uses, much broader assessments are required (Cousins et al., 2019). Although the toxicity and persistence of most PFAS are well-established, there is limited research on how potential alternatives can meet the diverse and demanding requirements of food packaging while avoiding unintended negative consequences.

Addressing this scientific knowledge gap requires a deeper exploration of how the technical and functional properties of alternatives compare to PFAS under varied conditions, as well as an assessment of regulatory, economic, and social impacts. To avoid potentially high costs of making errors, a granular assessment of all impacts under different risk management options, and a transparent balancing of social costs and benefits, remains indispensable for decision-making in many cases (Karinen et al., 2024).

The phase-out of PFAS can proceed along various paths, each with its own timeline and set of priorities. These timelines and priorities are largely influenced by the volume of PFAS in use and how broadly and openly they are dispersed. Given the significance and complexity of this task, it is essential to develop a detailed roadmap that outlines these different paths and their respective timelines. Currently, there is a lack of clear guidelines and frameworks for industries to transition from PFAS in the food packaging industry to PFAS-free alternatives, which defines the practical knowledge gap.

1.3 Research Objective and Research Questions

The objective is to identify key technical, regulatory, economic, and social challenges that hinder replacing PFAS with alternatives in the food packaging & food contact materials industry. Additionally, the aim is to propose effective strategies that stakeholders can implement or could have implemented at an earlier stage, to facilitate the transition from PFAS use to safe and sustainable PFAS-free alternatives in the food packaging & contact materials industry. This creates the following research question.

What are the key challenges for implementing PFAS-free alternatives in the food packaging & food contact materials industry?

The research sub-questions are:

1. Who are the key actors, networks, and institutions involved in the development and implementation of PFAS alternatives in the food packaging industry?
2. What factors hinder the transition towards sustainable and safe alternatives to PFAS in the food packaging & food contact materials industry?
3. What strategies can be implemented by stakeholders to overcome barriers and support the development and adoption of PFAS alternatives in the food packaging industry?

1.4 Approach

To better understand the dynamics within the PFAS industry, the TIS framework is applied to a case study of the food packaging industry. This framework supports the analysis of barriers that hinder the development and adoption of PFAS alternatives. The Technological Innovation Systems (TIS) approach is a framework used to analyze the development, diffusion, and utilization of new technologies (Hekkert et al., 2007). It focuses on the dynamics of innovation processes and identifies the key components and functions that drive system change. The TIS approach emphasizes the roles of various actors, networks, institutions, and the systemic interactions that influence innovation (Bergek et al., 2008). To better understand the dynamics within the PFAS industry, the TIS framework is applied to a case study of the food packaging industry. This framework supports the analysis of barriers that hinder the development and adoption of PFAS alternatives. The TIS approach is a framework used to analyze the development, diffusion, and utilization of new technologies (Hekkert et al., 2007). It focuses on the dynamics of innovation processes and identifies the key components and functions that drive system change. The TIS approach emphasizes the roles of various actors, networks, institutions, and the systemic interactions that influence innovation (Bergek et al., 2008).

1.5 Link to Complex Systems Engineering & Management

Replacing PFAS requires addressing technical, regulatory, economic, and social dimensions, which are inherently interdependent. This necessitates a socio-technical approach, to ensure that technical solutions align with regulatory frameworks and social acceptance. The persistence and widespread use of PFAS create complex environmental and health dynamics that are difficult to predict and manage, making systems engineering techniques essential for modeling these dynamics and designing effective interventions. Furthermore, the management of PFAS replacement involves coordinating multiple stakeholders, including regulatory bodies, industry players, and the public, which requires multi-actor coordination supported by systems engineering methodologies. Lastly, the significant policy and regulatory considerations in developing PFAS alternatives highlight the need for systems engineering tools to analyze and design regulatory frameworks that support technological innovation and adoption. Thus, the complex, interdisciplinary nature of the PFAS problem and the need for integrated technical, regulatory, and social solutions make it an excellent fit for the master's degree in Complex Systems Engineering and Management.

1.6 Report Structure

This report is structured as follows: Chapter 1 introduces the research problem, objectives, and methodology. Chapter 2 provides background information on PFAS and their regulation. Chapter 3 outlines the theoretical framework, focusing on the TIS approach. Chapter 4 details the research methods, while Chapters 5 and 6 present the structural and functional analysis results. Chapter 7 proposes strategies to overcome systemic barriers, followed by a discussion in Chapter 8. Finally, Chapter 9 concludes the study and suggests directions for future research.

2 State-of-the-art

2.1 What are PFAS?

PFAS are a diverse group of synthetic chemicals which do not occur naturally, are developed in the late 1940s and introduced widely for industrial and consumer applications due to their unique chemical properties (Panieri et al., 2022). The defining characteristic of PFAS is the carbon-fluorine bond, which is among the strongest in chemistry, contributing to their stability and resistance to degradation. Although a universal definition of PFAS has been changing constantly based on the scope, application and criteria adopted by different studies conducted on this broad category of substances, the Organisation for Economic Cooperation and Development (OECD) has come up with a universal definition in 2018. The OECD definition entails: fluorinated substances that contain at least one fully fluorinated methyl or methylene carbon atom (without any H/Cl/Br/I atom attached to it), i.e., with a few noted exceptions (represented by a carbon atom instead having H/Cl/Br/I atoms attached), any chemical with at least a perfluorinated methyl group -CF3- or a perfluorinated methylene group -CF2- is a PFAS (Panieri et al., 2022)

Since their initial development, the number of PFAS has expanded significantly, with estimates ranging from around 4,700 to over 12,000 different compounds identified (Brunn et al., 2023). This proliferation is attributed to industrial innovation, varied applications, and the emergence of new PFAS types to replace restricted substances (Brunn et al., 2023) (Schiavone and Portesi, 2023). The exact count of PFAS remains debated due to differences in classification, definitions, and detection methods (Schiavone and Portesi, 2023)

Chemical properties Due to the strong carbon-fluorine bond, PFAS substances do not break down even at high temperatures reaching several hundred degrees or when exposed to aggressive chemicals, which makes them highly valuable for various technical uses. The highly electronegative nature of fluorine contributes to the desirability of trifluoromethyl groups (-CF3) as structural components and gives many PFAS their water-repellent, oil-repellent, and dirt-repellent properties (Brunn et al., 2023). These attributes enable a wide range of industrial applications. Research by Gï et al. (2020) highlights that nearly every aspect of daily life and industrial processes involves fluorochemicals, with over 200 applications spread across 64 different use categories. Well-known applications in which PFAS are used are industrial processes, firefighting foams, textiles, food contact materials (including packaging), metal plating, consumer mixtures, ski wax, transport, applications of fluorinated gased, electronics and semiconductors, energy sector, construction products, lubricants, petroleum and mining, medical devices, cosmetics and other uses (Gï et al., 2020).

Barrier protection PFAS in food packaging is used for barrier protection for preventing grease and fat from penetrating paper and board materials. Two main types of barriers are utilized to achieve this: physical barriers and chemical barriers.

- Physical Barriers: These rely on the structure of the paper itself to block grease. Papers like Natural Grease-proof paper and vegetable parchment use tightly packed cellulose fibers to prevent grease from soaking in. Another approach to physical barriers involves adding a layer of aluminum or plastic, which protects the paper but makes recycling harder.
- Chemical Barriers: In this approach, chemicals are added to the paper to repel grease by reducing the surface energy, making it harder for grease to spread. Chemical barriers can be applied by adding substances to the paper pulp or as a surface coating. Traditional fluorinated chemicals (PFAS) are commonly used here, but there are also alternatives available. An overview can be found in Table 1 (Trier et al., 2018).

Type of alternative coating:
Starch
CMC
PVOH
Wax dispersions
HEC (hydroxyethylcellulose)
Copolymer (styrene-butadiene)
Chitosan
AKD (alkyl Ketene Dimer)
ASA (Alkenyl Succinic Andyhydride)

Table 1: Alternative coatings to PFAS in paper and board for food contact (Trier et al., 2018)

Classification of PFAS Chemically, PFAS can be broadly classified based on the length of their fluorinated carbon chains and their molecular structures. This classification leads to distinctions between short-chain PFAS, long-chain PFAS, and fluoropolymers. Short-chain PFAS typically have fewer than seven carbon atoms in their fluorinated chain, while long-chain PFAS have seven or more carbon atoms (Panieri et al., 2022). This structural difference influences their behavior in both environmental and biological contexts. Short-chain PFAS are more water-soluble and tend to move more readily through aquatic systems, whereas long-chain PFAS exhibit a higher potential for bioaccumulation due to their greater affinity for organic matter and proteins (Panieri et al., 2022). Fluoropolymers, a subgroup of PFAS, differ in that they are long-chain polymers where most hydrogen atoms in the carbon backbone are replaced with fluorine (Henry et al., 2018).

Toxicity of PFAS in human and environment The discovery of PFAS toxicity emerged as researchers and regulatory bodies observed their persistence in the environment and tendency to accumulate in living organisms (Panieri et al., 2022) This bioaccumulation occurs because the carbon-fluorine bonds resist metabolic and environmental breakdown processes. Long-chain PFAS, such as perfluorooctanoic acid (PFOA) and perfluorooctane sulfonate (PFOS), are particularly prone to accumulating in human blood, tissues, and the environment, contributing to concerns about their toxicity (Panieri et al., 2022). Short-chain PFAS, while more mobile, may pose risks due to their widespread distribution and potential effects at lower levels of bioaccumulation. The persistence of PFAS is primarily attributed to their stable carbon-fluorine bonds, which withstand environmental and biological degradation processes. This stability leads to continuous accumulation in both human and environmental systems, with these chemicals detected in air, water, soil, and wildlife.

Once PFAS enter the body through contaminated water, food, or products, they bind to proteins, particularly in the blood, liver, and kidneys (Brunn et al., 2023). This binding disrupts normal biological processes by interfering with receptor pathways and cellular function (ibid.). PFAS exposure is linked to liver damage, kidney function impairment, immune system suppression, and increased cholesterol levels. Research has also shown connections to developmental issues, reduced birth weight, and potential carcinogenic effects, particularly for long-chain variants like PFOA and PFOS (ibid.). As of September 2020, the European Food Safety Authority (EFSA) has set a tolerable weekly intake (TWI) of just 4.4 ng/kg body weight for a combination of key PFAS, including PFOA, PFOS, PFHxS, and PFNA (Panieri et al., 2022).

In the environment, PFAS pose risks to aquatic life at concentrations as low as a few micrograms per liter, affecting fish, invertebrates, and amphibians. The compounds can bioaccumulate and biomagnify in food chains, meaning that top predators, including humans, may experience amplified exposure . Studies have documented significant PFAS contamination in fish, wildlife, and even honeybees, which impacts ecosystems and food safety (Panieri et al., 2022).

These toxic effects are already evident in areas near industrial sites and regions where PFAS-containing products were used, such as fire-extinguishing foams(ECHA, 2023). For example, contamination has been noted around airfields and manufacturing sites, leading to polluted groundwater and soil (Brunn et al., 2023). PFAS's persistence is due to their resistance to environmental degradation, meaning they remain for decades or longer, making cleanup efforts difficult and costly. Research by Sunderland et al. (2019) has demonstrated that PFAS are present everywhere, as illustrated in Figure 2

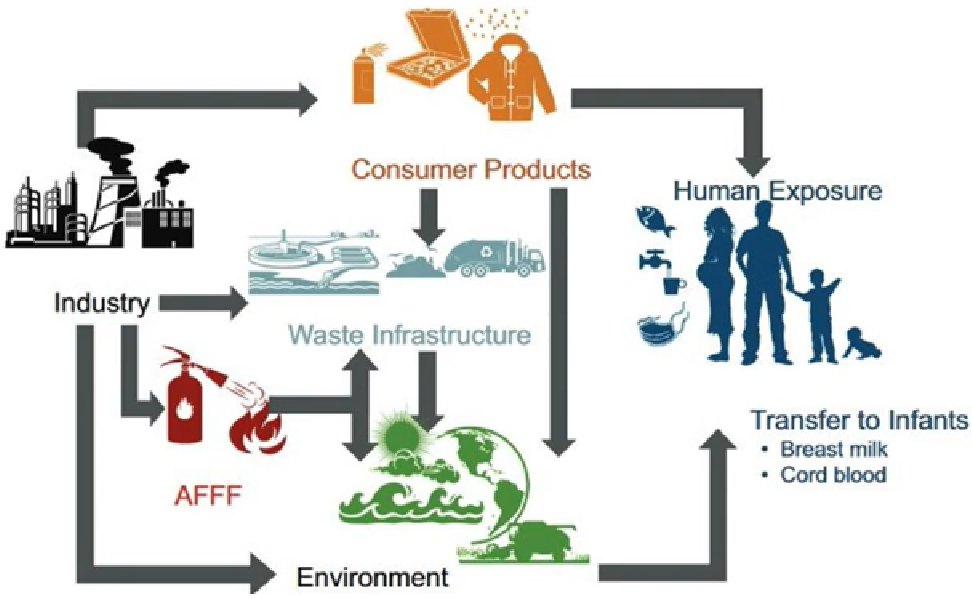

Figure 2: Overview of PFAS exposure pathways for different human populations outside of occupational settings by Sunderland et al. (2019)

2.2 Regulation of PFAS

The regulation of PFAS at the European level began in 2004 with restrictions on PFOS, which lasted until 2019, when broader legislation under Regulation (EU) 2019/1021 on persistent organic pollutants was enacted, banning PFOS and its derivatives with limited exceptions (Schiavone and Portesi, 2023). PFOS, being one of the most commonly used and well-researched PFAS at the time, exhibited clear indications of bioaccumulation and toxicity, including links to liver damage, developmental issues, and immunotoxic effects. Regulatory bodies chose to target PFOS first because it was one of the most pervasive long-chain PFAS, making it a logical starting point for addressing the broader issue of PFAS contamination (Gï et al., 2020). Over the years, additional measures were introduced, including EFSA's risk assessments and recommendations in 2008 and 2018, leading to stricter regulations, such as the 2022 proposal to ban PFAS in firefighting foams to prevent soil and groundwater contamination. Consequently, the production and use of long-chain PFAS have significantly decreased, but many homologous substances have substituted them, including short-chain PFAS (Reinikainen et al., 2024).

REACH procedure Denmark, Germany, the Netherlands, Norway, and Sweden made a major move to combat PFAS contamination in Europe by submitting a proposal to the European Chemicals Agency (ECHA) seeking to ban PFAS under the REACH regulation. The REACH process stands for Registration, Evaluation, Authorisation, and Restriction of Chemicals. It is a comprehensive regulatory framework adopted by the European Union to manage and control the risks associated with chemical substances to ensure a high level of protection for human health and the environment (Rudin et al., 2023). These five authorities identified uncontrolled risks associated with the production, marketing, and use of these substances, emphasizing the need for intervention by the EU and the European Economic Area (EEA). The proposal is driven by increasing evidence of the harmful environmental and health impacts associated with PFAS contamination, which is not adequately controlled by existing measures. The proposal includes a comprehensive assessment of PFAS's properties, including their extreme persistence, bioaccumulation potential, and toxicity.

The regulation aims to phase out PFAS in non-essential applications while allowing for controlled use in critical sectors where alternatives are not yet feasible. This is determined via the concept of essential use of Cousins et al. (2019).

Concept of essential use Due to the high diversity in PFAS applications, each PFAS application serves a different purpose across various segments and products. Consequently, a single PFAS alternative cannot replace all PFAS uses, as each serves distinct functions (Cousins et al., 2022). In the article of Cousins et al. (2019), the authors examine the functional characteristics of PFAS in various products and categorize their essentiality as non-essential, substitutable, or essential.

1. Non-essential uses of PFAS are those that are not critical for health, safety, or the functioning of society. The use of PFAS in these applications is primarily driven by market opportunities rather than necessity. Although these uses may provide benefits, they are not indispensable and can be prohibited without significant impact. Eliminating non-essential uses of PFAS could serve as a starting point for initiating a global phase-out process. In the article of Karinen et al. (2024), a social consensus among citizens is stated that PFAS used in recreation, household, and personal care products can be banned without major issues.

2. Substitutable uses are those considered essential due to their important functions, but for which alternatives now exist that can provide equivalent functionality and adequate performance. Although it may be necessary to increase awareness and availability of these alternatives, there are no fundamental obstacles to replacing PFAS in these applications.

3. Essential uses are those deemed necessary for health, safety, or other critical purposes where alternatives are not yet established. Innovative research and development are necessary to transition these applications into the substitutable category. Currently, PFAS uses categorized as non-essential can be restricted through EU policy. While essential uses remain in the early stages of development and cannot yet be phased out, the adoption of alternatives in the substitutable category can be implemented in new products.

In general, products in the first and second categories are fully banned. Products of the third category use derogations up to be possible for up to 12 years (5 years and 12 years, respectively, after the end of a transition period of 18 months). To ensure a transparent and inclusive process, ECHA launched a public consultation phase. During this period, stakeholders such as industry representatives, NGOs, and the general public were invited to provide input, share additional data, and offer feedback on the proposed restrictions. Industries were given the opportunity to request a derogation period if they could demonstrate that no viable alternatives exist in their specific segment or that technical or economic factors prevent replacing their PFAS with a PFAS-free alternative. An overview of the categories can be found in figure 3. Examples of derogation timeframes chosen are

- Food contact materials for industrial food and feed production. Alternatives in this industry are under development, but not available at entry into force yet. Therefore, a derogation time of 5 years has been provided.

- Implantable medical devices. In this industry, identification, development and certification of alternatives are still needed. In this industry, a derogation time of 12 years has been provided.

Use	Category[a]
Personal care products including cosmetics	1
Ski waxes	1
Fire-fighting foams (commercial airports)	2
Fire-fighting foams (military)	2 or 3
Apparel (medical: long operations)	3
Apparel (protective clothing oil and gas industry)	3
Apparel (medical: short operations, everyday)	2
Apparel (military: occupational protection)	2 or 3
Waterproof jacket (general use)	2
Easy care clothing	1
Food contact materials	1, 2 or 3
Non-stick kitchenware (fluoropolymers)	1 or 2
Medical devices (fluoropolymers)	1, 2 or 3
Pharmaceuticals	2 or 3
Laboratory supplies, equipment and instrumentation	1, 2 or 3
Perfluorosulfonic membranes in fuel cells	2
Perfluorosulfonic membranes in chlor-alkali process	3

[a] Note that the categories in the above table represent the current evaluation and may change in the future.

Figure 3: Concept of essential use by Cousins et al. (2019)

The proposal is examined by ECHA's Risk Assessment Committee (RAC) and Socio-Economic Analysis Committee (SEAC). RAC focused on evaluating the scientific evidence of the risks posed by PFAS and the effectiveness of the proposed restrictions. SEAC analyzed the socio-economic implications, weighing the costs and benefits of banning PFAS against the potential impact on industries and society. On 7 February 2023, ECHA released this comprehensive proposal, marking one of the most extensive regulatory efforts in EU history (Schiavone and Portesi, 2023). The restriction targeting all PFAS as a comprehensive group aims to limit as many uses as feasibly possible to reduce emissions and human and environmental exposure to PFAS, encompass currently unidentified PFAS substances and applications, and prevent the substitution of restricted PFAS with other PFAS that pose similar risks (Wollin et al., 2023).

2.3 Assessment of PFAS residue levels in Food Packaging Products

A European study conducted in 2021 by eight civil society organizations investigated the presence of PFAS in disposable food packaging and tableware, focusing on products sold in six European countries: the Czech Republic, Denmark, France, Germany, the Netherlands, and the United Kingdom (Strakova et al., 2021). The primary aim was to gather evidence on the widespread use of PFAS in these products and to assess background contamination levels. The research also aimed to differentiate between intentionally treated PFAS and non-intentionally treated PFAS in these materials.

Key findings of the study revealed several concerning trends:

- Widespread Use of PFAS: PFAS chemicals are commonly found in disposable food packaging and tableware across Europe. This includes packaging from popular fast-food chains and restaurants, indicating a broad reliance on these chemicals for their grease- and water-resistant properties.

- High Concentrations in Moulded Fibre Products: The highest PFAS concentrations were consistently detected in moulded fibre products such as bowls, plates, and food boxes. These products are often advertised as biodegradable or compostable, but the inclusion of non-degradable PFAS chemicals starkly contradicts these claims. Addressing this inconsistency is an urgent priority.

- Unidentified PFAS: Most of the total PFAS load in food packaging remains unidentified. While it is possible to determine the presence of PFAS, identifying specific types of PFAS chemicals often proves challenging.

The study highlighted the inherent environmental risks of disposable food packaging and tableware, which are designed for single use. Produced in high volumes with rapid turnover rates, these items contribute to PFAS emissions throughout their lifecycle, from manufacturing to disposal (Strakova et al., 2021). This underscores the pressing need to address the use of PFAS in such products to mitigate their environmental and health impacts (Schaider et al., 2017).

3 Theoretical Background

This chapter outlines the research approach,and describes the data collection methods and analytical tools used. Furthermore, a research overview is given in figure 4.

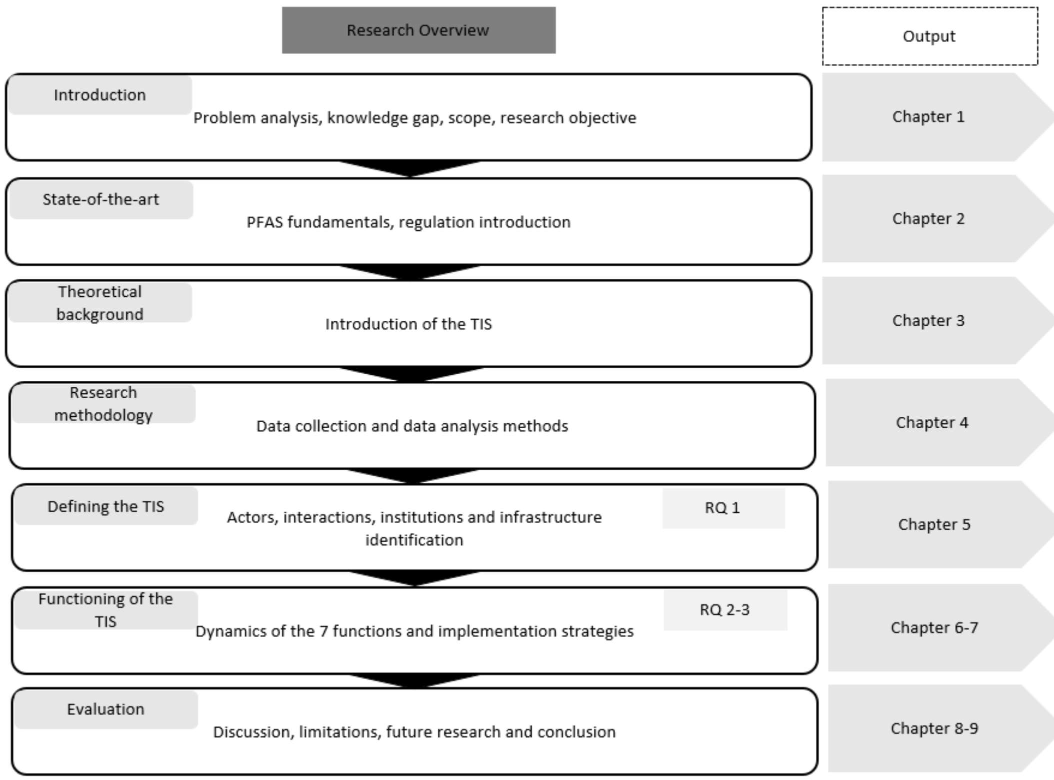

Figure 4: Research Overview

3.1 Technological Innovation Systems Approach

To figure out what are the key challenges the adoption of alternatives to PFAS in the food packaging & contact materials industry, the TIS approach is applied. The TIS approach is a framework used to analyze the development, diffusion, and utilization of new technologies (Hekkert et al., 2007). It focuses on the dynamics of innovation processes and identifies the key components and functions that drive technological change. The TIS approach emphasizes the roles of various actors, networks, institutions, and the systemic interactions that influence innovation (Bergek et al., 2008). By mapping the structure of the innovation system, analyzing the functional dynamics, and identifying barriers and enablers, the TIS framework provides a comprehensive understanding of how technological innovations progress and can be effectively supported (Hekkert et al., 2007).

3.1.1 Application of the TIS to the case-study

To apply the TIS approach, the food packaging industry is investigated as a case study. Case studies are used to generate deep, multi-faceted understanding of complex issues in real-life contexts (Crowe et al., 2011). In this case, the implementation of difficult-to-replace alternatives to PFAS in the food packaging & contact materials industry is existent but not fully developed. The case-study approach allows for in-depth analysis and provides practical insights into how systemic issues can be addressed to speed up the adoption of PFAS alternatives (Crowe et al., 2011).

The main driver to the development of alternatives is the necessity to replace harmful substances due to their toxic nature. This means that the innovation process for PFAS alternatives is heavily influenced by regulatory pressures and public health concerns rather than market-driven enhancement goals. Still, the TIS approach is a suitable approach to apply as it maps out the dynamic processes and interactions among various actors, institutions, and technologies (Hekkert et al., 2007). This is crucial for understanding how the shift from PFAS to safer alternatives can be effectively managed, considering the complexities involved in replacing such widely used chemicals. Furthermore, TIS focuses on identifying "system failures" or weaknesses in the innovation system that hinder the development and diffusion of new technologies, which aligns well with the challenges faced in finding and implementing PFAS alternatives (Hekkert et al., 2007). At last, TIS provides a structured framework for policymakers to design interventions that can facilitate the transition to PFAS alternatives (Bergek et al., 2008).

Identify Structural Components of the TIS Bergek et al. (2008) identified various stages within the TIS. However, this study focuses solely on the structural dimensions and functions, as these aspects are most relevant to addressing the research questions. According to Wieczorek and Hekkert (2012), four key structural components form the foundation of a TIS. These components are as follows:

- Actors play a crucial role in driving innovation activities. They can be categorized based on their roles in economic activities, including social groups, governmental bodies, non-governmental organizations (NGOs), multinational corporations, academic institutions, and other entities such as judicial, economic, and intergovernmental organizations. These actors contribute to the innovation system in various capacities.

- Institutions consist of shared practices, norms, and procedures that guide behavior in recurring situations (referred to as soft institutions) and are often shaped by formal regulations, policies, and strategies (known as hard institutions). Unlike enterprises, institutions derive their structure and functions from the unique geographic and cultural contexts in which they operate.

- Interactions refer to the connections and relationships among actors. Although the term ”network” is often used in research to describe these linkages, interactions can also occur independently of established networks. In the early stages of system development, networks may not yet exist, but informal exchanges between actors can still take place.
- The concept of infrastructure within the context of innovation systems is not uniformly defined in academic literature. Generally, infrastructure refers to the availability of resources such as funding, subsidies, or development programs. Both physical infrastructure and intellectual resources are critical in shaping the evolution and competitive dynamics of technologies.

These four structural elements collectively influence the functioning and development of TIS, highlighting the interconnectedness of actors, institutions, interactions, and resources.

Map the Functional Pattern of the TIS The objective is to describe the functional dynamics of the TIS by assessing seven key functions of Wieczorek and Hekkert (2012).

- **Entrepreneurial activity**: Entrepreneurial activity is a cornerstone of any innovation system; without entrepreneurs, such a system cannot function effectively. Entrepreneurs play a crucial role by transforming the potential of new knowledge, networks, and markets into tangible actions that generate and capitalize on business opportunities. These entrepreneurs may be new entrants with a vision for emerging markets or established companies diversifying their strategies to leverage new developments. The presence of active entrepreneurs is a primary indicator of the performance of an innovation system. If entrepreneurial activity is lacking, the root causes may lie within the other six functions of the system.

  In this context, interviewing companies that sell alternatives to PFAS is particularly insightful. The ban on all PFAS presents significant opportunities for companies providing alternatives. This situation prompts important questions: Why are stakeholders in the food packaging & contact material industry so insistent that PFAS cannot be replaced, even though literature suggests that alternatives are available? Furthermore, it is intriguing why companies offering these alternatives are not more proactive in promoting their products as viable replacements, despite the considerable financial potential they could harness.
- **Knowledge Development**: Evaluate the knowledge base and its evolution, including scientific, technological, and market knowledge.
  # Three typical indicators to map this function over time are: 1) R&D projects, 2) patents, and 3) investments in R&D.
- **Knowledge Dissemination**. According to Wieczorek and Hekkert (2012), the essential function of networks is the exchange of information. This is important in a strict R&D setting, but especially in a heterogeneous context where R&D meets government, competitors, and market.

This function can be analysed by mapping the number of workshops and conferences devoted to a specific technology topic, and by mapping the network size and intensity over time. Given that this thesis does not primarily focus on a new technology, this function may not be particularly relevant in this context.

- **Guidance of the Search**. By counting the number of articles that are positive or negative regarding the new technology development, the state of the debate can be assessed. A strong discussion about the potential benefits of new technology is likely to hamper future developments, while a strong emphasis on the positive aspects is likely to stimulate technology development.

  # This function can be analysed by mapping specific targets set by governments or industries regarding the use of a specific technology and by mapping the number of articles in professional journals that raise expectations about new technological developments.

- **Market Formation**. Most inventions are relatively crude and inefficient at the date when they are first recognized as constituting a new innovation. They are, of necessity, badly adapted to many of the ultimate uses to which they are put. Therefore, new inventions may offer only very small advantages, or perhaps none at all, over previously existing techniques. Because of this, it is important to create protected space for new technologies.

  # This function can be analysed by mapping the number of niche markets that have been introduced, specific tax regimes for new technologies, and new environmental standards that improve the chances for new environmental technologies.

- **Resources mobilization**: Evaluate the mobilization of human, financial, and complementary resources necessary for the TIS.

  # This function is difficult to map by means of specific indicators over time. In this case the best suited method to create insight in the fulfillment of this function is to detect, by means of interviews, whether or not inner core actors perceive access to sufficient resources as problematic.

- **Creation Of Legitimacy/counteract Resistance To Change** # This function can be analysed by mapping the rise and growth of interest groups and their lobby actions. In this thesis, there is a bigger lobby on the industry side. However, on the PFAS alternatives side, there might not be a big lobby, which makes this function not the most relevant function in this case.

Once the functional pattern of the TIS is mapped, systemic problems can be identified. Systemic problems refer to barriers or failures within an innovation system that hinder its development and functionality (Wieczorek and Hekkert, 2012). These issues include challenges related to actors' capabilities, the presence and quality of institutions, interactions between stakeholders, and the availability of infrastructure. They negatively influence the direction and speed of innovation processes. The goals of systemic instruments are to address these systemic problems by creating conditions conducive to innovation (Wieczorek and Hekkert, 2012). This includes ensuring the participation of relevant actors, fostering capabilities, stimulating interactions, improving institutional presence and quality, and enhancing infrastructure. These tools aim to support the functioning of the innovation system as a whole, facilitating the desired technological and systemic transitions., the next logical step is to explore strategies that stakeholders can use to address these barriers (Wieczorek and Hekkert, 2012). Figure 5 gives an overview of the systemic problems with its aligned systemic instrument goals.

System function	Structural element	Systemic problem	(Type of) systemic problem	Systemic instrument goals
F1: entrepreneurial activities	Actors	Actors problems	Presence?	Stimulate and organise the participation of relevant actors (1)
			Capabilities?	Create space for actors capability development (2)
	Interactions	Interaction problems	Presence?	Stimulate occurrence of interactions (3)
			Capacity?	Prevent too strong and too weak ties (4)
	Institutions	Institutional problems	Presence?	Secure presence of hard and soft institutions (5)
			Intensity?	Prevent too weak and too stringent institutions (6)
	Infrastructure	Infrastructural problems	Presence?	Stimulate physical, financial and knowledge infrastructure (7)
			Quality?	Ensure adequate quality of infrastructure (8)
F2: knowledge development etc.	Actors	Actors problems	Presence?	Stimulate and organise participation of relevant actors (1)
			Capabilities?	Create space for actors capability development (2)
	Interactions	Interaction problems	Presence?	Stimulate occurrence of interactions (3)
			Intensity?	Prevent too strong and too weak ties (4)
	Institutions	Institutional problems	Presence?	Secure presence of hard and soft institutions (5)
			Capacity?	Prevent too weak and too stringent institutions (6)
	Infrastructure	Infrastructural problems	Presence?	Stimulate physical, financial and knowledge infrastructure (7)
			Quality?	Ensure adequate quality of infrastructure (8)

Figure 5: Innovation policy framework by Wieczorek and Hekkert (2012)

4 Research Methodology

4.1 Data collection

To gather information from all stakeholders in the TIS, five different data sources have been utilized. These information sources include: scientific articles, scientific reports, the Annex, semi-structured interviews and stakeholder reactions to the PFAS ban proposal,.

4.1.1 Literature research

In the methodology section of literature research, Scopus was utilized as the primary tool for article selection. Initially, a search query was defined as TITLE-ABS-KEY (PFAS) AND TITLE-ABS-KEY (alternative) OR TITLE-ABS-KEY (replacement) OR TITLE-ABS-KEY (substitution), excluding non-English or Dutch yielding 334 articles. Considering the evolving nature of alternatives of PFAS and the high amount of results, the time frame was set from 2021 to 2024, yielding 254 articles. As can be seen in figure 7 in chapter 6, in 2021, reseach into PFAS rapidly increased since then. The articles were selected by reviewing titles and abstracts, focusing on studies that investigate the challenges and strategies for finding alternatives to PFAS in the food packaging & food contact materials industry. Since not so many articles focused specifically on challenges and strategies of food packaging & food contact materials, many articles could be excluded. From the initial 254 articles, the following refinement process is conducted.

- Articles were included only if they directly addressed the challenges and strategies associated with implementing alternatives to PFAS in the food packaging and food contact materials industry.
- If multiple articles covered similar findings or perspectives, the most comprehensive and recent article was retained, while the others were excluded to avoid redundancy.
- Articles that failed to align with the specific objectives of understanding barriers and strategies for PFAS alternatives in food packaging were excluded, even if they were broadly related to PFAS.

Out of 254 articles, 34 were selected after undergoing the refinement process. Subsequently, these 34 articles were thoroughly examined, leading to the exclusion of 14 articles that were not pertinent to the refinement process. Furthermore, 5 additional article were identified through forward snowballing, resulting in a final literature overview of 25 selected articles, which are listed in figure 6.

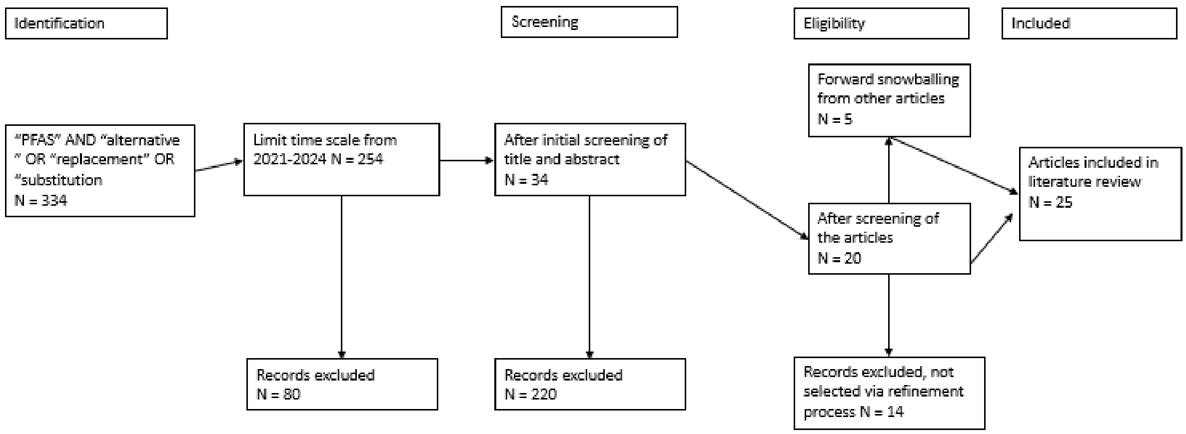

Figure 6: Literature research methodology

4.1.2 Scientific reports

In addition to scientific articles, scientific reports are also used as key sources for information gathering. Published by reputable organizations, government agencies, and research institutions, these reports offer an in-depth, well-rounded perspective on PFAS in the food packaging industry, addressing a broad range of topics such as regulatory issues, environmental and health impacts, and industry practices. A major benefit of incorporating scientific reports is their comprehensive coverage; unlike scientific articles, which typically focus on narrower research questions, these reports examine PFAS from multiple angles, providing valuable insights into the complex relationships between industry, policy, and science (Verschuren and Doorewaard, 2010). This breadth of information adds depth and context to the more specific findings of scientific articles.

4.1.3 Annex

In addition to scientific articles, reports, and stakeholder feedback, the annex of the ECHA's PFAS ban proposal was also used as an information source for this research (ECHA, 2023). The annex provides detailed insights from regulatory bodies, offering an overview of the scientific and technical evidence that supports the proposed restrictions on PFAS use. By consulting the annex, information directly from the regulators is gathered, including their reasoning for the proposed measures, the assessment of risks associated with PFAS in food packaging, and the regulatory impact on different industries.

4.1.4 Semi-Structured Interviews

As a last information source, semi-structured interviews are conducted with key actors in the defined TIS. Semi-structured interviews are suitable for this research because they provide a flexible yet guided approach to data collection (Verschuren and Doorewaard, 2010). This method allows for the exploration of predetermined questions while also giving the freedom to probe deeper into interesting or unexpected topics that arise during the conversation. This flexibility is particularly important given the innovative and relatively unexplored nature of the barriers to implementing alternatives to PFAS in the food packaging industry. Semi-structured interviews facilitate the collection of detailed and nuanced information, capturing both the broad trends and specific insights necessary for a thorough analysis (Verschuren and Doorewaard, 2010).

Interview code	Stakeholder type	Organisation type	Interviewee type	Date
BO	Brand owner	Distributor of alternatives	Marketing manager	20-9-2024
PR1	Regulator	Policy and regulatory stakeholder	Network and policy coordinator	24-9-2024
PR2	Regulator	Policy and regulatory stakeholder	Regulation coordinator	25-9-2024
CI1	Chemical industry	Representative of the chemical industry	Policy advisor	7-10-2024
AE	Academia	University	Professor of environmental ecology	9-10-2024
NG	NGO	NGO	Head of corporate sustainability	9-10-2024
MF1	Manufacturer & brand owner	Producer and seller of alternatives	R&D director	10-10-2024
MF2	Manufacturer & brand owner	Network organisation in food packaging industry	Technical consultant	11-10-2024
CI2	Chemical industry	Representative of the chemical industry	Sustainability manager	14-10-2024
MF3	Manufacturer & brand owner	Producer and seller of alternatives	R&D director	17-10-2024
MF4	Manufacturer & brand owner	Producer and seller of alternatives	CEO and R&D director	30-10-2024

Table 2: Participant selection

Interview questions In the set of interview questions, a distinction has been made between companies that sell alternatives to PFAS and other stakeholders in the stakeholder analysis. For companies offering alternatives to PFAS, the focus is primarily on their entrepreneurial activities. In contrast, interviews with other stakeholders are centered on the broader transition of the entire alternatives-to-PFAS system within the food packaging & food contact materials industry. Given the semi-structured nature of the interviews, stakeholder-specific questions were also be included. The primary set-up of the interview questions can be found in Appendix A

4.1.5 Stakeholder reactions on the proposal of the PFAS ban

After the ECHA released the proposal for the PFAS ban, a six-month consultation period from 22 March 2023 to 25 September 2023 was opened to allow stakeholders, including industry representatives, environmental groups, scientists, and the public to provide feedback. Stakeholders submitted their responses through the ECHA's online portal, where all submissions were organized and published for transparency (ECHA, 2023). These collected reactions were made publicly accessible, and have been analyzed as part of the information-gathering proces to identify recurring industry concerns, such as technical challenges, economic impacts, and the feasibility of alternative solutions, which are often central to industry perspectives on the proposed ban. During the six-month consultation period on the proposed PFAS ban, the ECHA received over 5,600 comments from more than 4,400 organizations, companies, and individuals. To identify relevant responses focused on PFAS in the food packaging industry, all comments were scanned using a text search for the term "food." This initial screening yielded 215 responses that appeared useful for analysis within the context of food packaging. However, nearly all of these responses focused on fluoropolymers, which, while technically classified as PFAS, differ significantly from the long- and short-chain PFAS typically used in food packaging and food contact materials. Unlike smaller PFAS compounds, which are mobile, bioaccumulative, and more likely to migrate into the environment or human systems, fluoropolymers are less prone to leaching or direct toxicity but remain environmentally persistent (Henry et al., 2018). This research excludes fluoropolymers due to their differing characteristics, minimal relevance to food packaging, and focus on smaller PFAS compounds that pose greater direct risks to human health and the environment. By targeting PFAS commonly used as coatings and additives in food packaging, the study aims to address the most immediate challenges in transitioning to safer alternatives.After further refinement, only 6 responses (N=6) were ultimately selected as relevant and included as sources for this research, which are number [5885], [6633], [6832], [7590], [7803] and [9387].

4.2 Data analysis

4.2.1 Qualitative content analysis

Scientific articles and scientific reports are analyzed through qualitative content analysis, allowing for the systematic examination of themes, patterns, and insights relevant to PFAS use in food packaging. This approach helps identify key challenges, strategies, and perspectives presented in the literature, contributing to a comprehensive understanding of the topic (Verschuren and Doorewaard, 2010).

4.2.2 Coding Methodology

To analyze the arguments gathered from the stakeholder reactions, the annex and the semi-structured interviews, the reactions of the stakeholders are coded.

This study explores the factors hindering the transition towards PFAS free alternatives in the food packaging & contact materials industry. Via thematic coding, the analysis uncovers the main problems and challenges that the stakeholders in the TIS face in relation to the PFAS ban. Understanding the critique of the industry, along with the associated argumentation, provides insights into the factors hindering the transition towards safe and sustainable PFAS-free alternatives.

The coding process is outlined in four steps based on the article of Hirt (2024):

1. First, all information sources are identified and collected.
2. Secondly, a content analysis of the collected documents is conducted via systematically reviewing the text to identify key arguments in an inductive approach. The arguments are classified into 6 categories. Coding the data is performed in the software named ATLAS.ti.

3. Thirdhly, a thematic analysis is executed to group similar arguments into broader categories and themes. By categorizing the arguments into themes, the overarching issues and concerns that stakeholders have regarding the PFAS ban can be better understood and structured.

4. Finally, the findings are interpreted by synthesizing the themes and categories. This step involves drawing connections between the arguments presented by the industry, the ECHA and the literature. The goal is to understand how these arguments might influence the final decision-making process regarding the PFAS ban and to identify any potential gaps or areas for further research.

5 Structural analysis results

This chapter defines the institutions and actors that play a role in the TIS of PFAS within the food packaging industry. Due to the variable nature of interactions and the unstable place of an infrastructure as structural component of innovations, it is challenging to precisely define stakeholder interactions and infrastructures at this stage. Therefore, these interactions and infrastructures are further explored in the functional analysis.

5.1 Institutional development of PFAS

To trace the origins of the institutional development of PFAS in the food packaging, it is required to look beyond the food packaging industry and consider the institutions of the broader PFAS industry. As noted in the introduction, PFAS use in industrial applications began in the 1950s. By the 1990s, growing evidence emerged about the increasing toxicity of PFAS and their accumulation in both humans and the environment.(Prevedouros et al., 2006). However, the attention of the scientific community has largely increased, since the last 15 years.

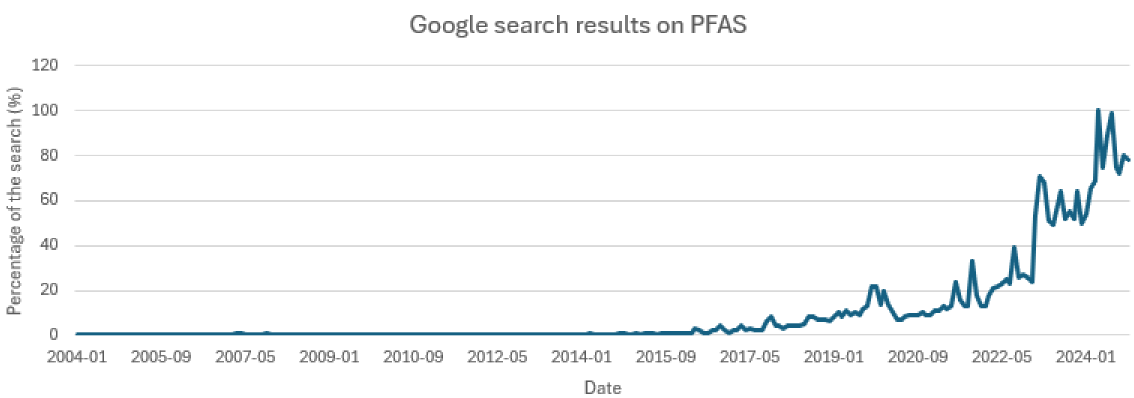

Figure 7: Interest over time with the word "PFAS" in Google searches since 2015. (https://trends.google.com/trends/explore?date=all&q=PFAS (accessed on 4 November 2024))

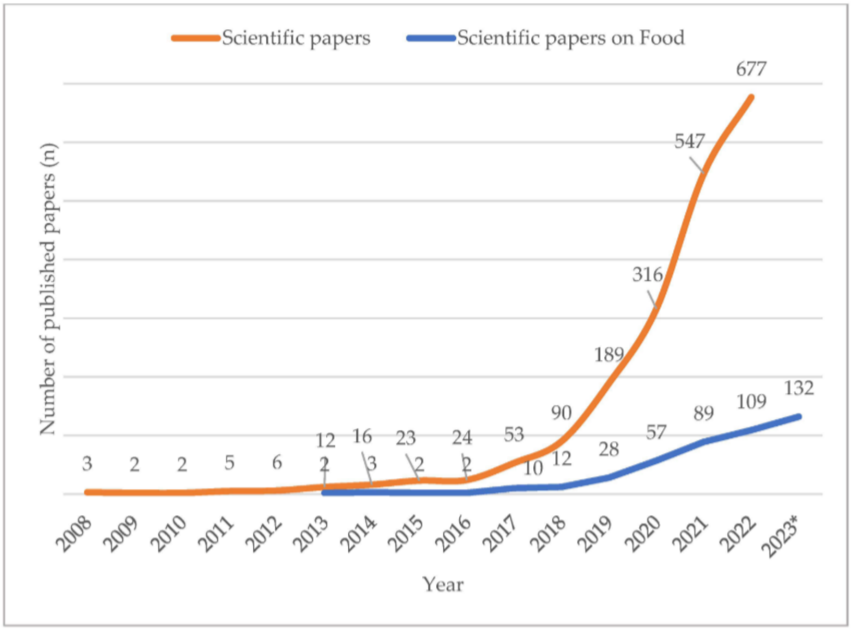

Figure 8: Chart for scientific papers and scientific papers on food published with the words "PFAS" and "food"

The development of institutions addressing PFAS contamination has been gradual, influenced by increasing awareness of the associated risks. At the European level, the first major step was taken in 2004 when the European Union introduced regulations to monitor and control PFOS production and commercialization, which remained valid until 2019. This marked the beginning of institutional attention to PFAS in Europe (Schiavone and Portesi, 2023).

By 2018, the European Food Safety Authority (EFSA) published a risk assessment linking human health concerns to PFOS and PFOA found in food (The European Commission, 2019). EFSA noted that these chemicals were present in the blood of almost all individuals tested, highlighting widespread exposure. This prompted discussions on the need for improved analytical methods and legislative measures (Schiavone and Portesi, 2023). This period was a start in rapidly shaping the transition toward stricter PFAS regulations.

In 2019, the Norwegian Environment Agency proposed listing PFHxS and its related compounds under the Stockholm Convention on Persistent Organic Pollutants (POPs) (Steindal and Grung, 2021). Simultaneously, European committees, such as the Committee for Risk Assessment (RAC) and the Committee for Socio-economic Analysis (SEAC), emphasized the necessity for a unified strategy to address the risks posed by PFAS . This included considerations for products and mixtures containing PFHxS and its derivatives, moving beyond national rules toward a broader European approach (Steindal and Grung, 2021) (Schiavone and Portesi, 2023).

The European Commission further strengthened its stance in February 2022, proposing a ban on PFAS in firefighting foams across the European Union (Steindal and Grung, 2021). This was a response to the increasing contamination levels detected with advancing technologies and the environmental and health risks associated with PFAS. The European Chemicals Agency (ECHA) evaluated several strategies for reducing these risks, culminating in a proposal to restrict the use, marketing, and formulation of PFAS in firefighting foams, with specific transition periods for industries. By 2023, ECHA had expanded its focus by listing additional PFAS compounds, such as PFHpA, as substances of very high concern, signaling a preventive approach to avoid replacing restricted PFAS with similarly harmful alternatives (Schiavone and Portesi, 2023).

Meanwhile, EFSA released a 2020 report identifying key food categories, including fish, fruit, and eggs, as significant contributors to human exposure to PFOS, PFOA, and related compounds (Gï et al., 2020). This reinforced the need for stricter oversight in food production and packaging materials.

Globally, efforts to regulate PFAS have varied. In the United States, Maine became the first state in 2021 to ban products containing intentionally added PFAS, inspiring other states to introduce similar measures (Schiavone and Portesi, 2023). In China, progress has been slower. In November 2020, PFOA and 17 other compounds were added to a list of Priority Control Chemicals, marking an initial step toward environmental risk control. By October 2021, China's Ministry of Ecology and Environment had drafted plans to manage new pollutants, including PFOA (Schiavone and Portesi, 2023). However, China still lags in PFAS regulation compared to Europe and the U.S., creating challenges as many food packaging materials are imported from China, where weaker regulations remain a big concern.

5.2 Institutional development of PFAS in the food packaging industry

Over time, the types of fluorochemicals used in paper and board packaging have evolved. Initially, long-chain PFAS compounds were widely used but were phased out in the 2000s (Cousins et al., 2019). Current products often rely on short-chain fluorotelomer-based polymeric products. These are side-chain fluorinated polymers containing perfluoroalkyl side chains, typically with six perfluorinated carbons, and poly- and perfluoropolyethers. While the chemical manufacturing industry asserts that short-chain fluorinated products are safe, there are concerns about their potential to migrate into food and harm human health (Trier et al., 2018).

In response to these risks, non-fluorinated alternatives have emerged in recent years. For instance, COOP Denmark A/S, a Danish consumer goods retailer, has successfully eliminated PFAS from all its products since September 2014 (Cousins et al., 2019). Substituting PFAS in food packaging requires tailored approaches due to differences in materials and performance requirements. Strategies for paper and board packaging, for example, differ significantly from those for textiles and may also vary among specific food packaging applications (Curtzwiler et al., 2021).

Efforts to regulate PFAS in food packaging have progressed unevenly across Europe. Although the EU Regulation (EC) No 1935/2004 sets a general safety standard for materials in contact with food, there are no specific harmonized safety rules for many types of food packaging, including paper and board (The European Commission, 2019). As a result, individual countries have implemented their own rules, leading to varying levels of protection across Europe.

Denmark is the only European country to have implemented a specific ban on PFAS in food packaging made from paper and board. Effective since July 2020, Denmark's regulation prohibits both direct PFAS applications—such as adding PFAS for water or grease resistance—and indirect sources, such as PFAS contamination from inks or recycled materials (Strakova et al., 2021). This proactive approach sets an example for other nations. Since 2020, the governments of Denmark, Sweden, Germany, and the Netherlands have started developing an EU-wide restriction of all non-essential uses of PFAS with the support of the ECHA, that led to submission of the proposed ban in 2023 (Strakova et al., 2021).

Efforts to regulate PFAS in food packaging have progressed unevenly across Europe (Trier et al., 2018). Although the EU Regulation (EC) No 1935/2004 sets a general safety standard for materials in contact with food, there are no specific harmonized safety rules for many types of food packaging, including paper and board (Strakova et al., 2021). As a result, individual countries have implemented their own rules, leading to varying levels of protection across Europe (Strakova et al., 2021).

5.3 Actors

- Manufacturers are the key players in the transition to PFAS-free alternatives with high power and high interest because they control the production processes and have the technical capacity to innovate and implement new materials (AE). Their decisions directly influence the availability and quality of PFAS-free products in the market. As the creators of food packaging materials, they have the unique ability to adapt technologies, invest in research and development, and scale up production of alternatives. Furthermore, manufacturers are at the intersection of the supply chain, responding to both regulatory pressures and the demands of brand owners and consumers. Without their active engagement and entrepreneurial activity, the transition to sustainable alternatives cannot be fully realized. Their role is essential in overcoming technical, economic, and logistical barriers to ensure a smooth shift away from PFAS (NG).

  There is a clear distinction between larger and smaller companies in their approach to transitioning toward PFAS-free alternatives. Larger companies with strong sustainability commitments, particularly those focusing on biodegradable packaging or plant-based materials, have often taken the lead in this transition. Their dedicated R&D capabilities provide them with the resources and expertise needed to innovate and respond effectively to emerging demands (AE).

  In contrast, smaller companies, which may lack the in-house expertise of their larger counterparts, often rely on external collaboration or specialized knowledge to develop PFAS-free alternatives. However, their inherent flexibility allows them to adapt more rapidly to market changes and regulatory demands. Startups and smaller firms have become key frontrunners in niche areas, such as water- and grease-resistant paper, where alternative polymers are being utilized. By anticipating future regulations, these agile companies have strategically positioned themselves to address the growing demand for PFAS-free solutions (PR2).

- Consumers are the final recipients of food packaging products, including restaurants, supermarkets and food manufacturers. As individual stakeholders, consumers have limited direct power over the industry, as they do not control production or regulatory decisions. Consumers have a moderate to low interest in the use of PFAS in food packaging because their primary focus is usually on the cost and the quality, safety, and convenience of the food itself rather than the specific materials used in packaging (MF1). Prominent entities that count as consumers in this context include major fast-food chains and restaurants offering takeaway services, such as McDonald's (Strakova et al., 2021).

- Brand owners include companies that sell consumer products and are responsible for the final packaging design and materials used for their products. Brand owners have a direct relationship with consumers and are sensitive to public perception and consumer demand for safer, more sustainable packaging. Brand owners have moderate to high power because they can influence their suppliers, set the standards for packaging materials, and drive market trends. Brand owners have a high interest in the regulation and phase-out of PFAS due to their potential impact on brand reputation and legal liabilities (BO).

- The chemical industry includes companies that produce PFAS chemicals, alternative chemical solutions, and raw materials used in the food packaging sector. The chemical industry holds high power due to its control over the supply of both PFAS and alternative chemicals (CI1). Companies with a large market share can influence market trends and shape the direction of the transition toward PFAS-free products. The chemical industry has a high interest in the regulation of PFAS because it affects their core products, market strategies, and revenue (CI2). Well-known companies in the chemical industry include 3M, Chemours and Solvay.

- Regulators, including government agencies and public authorities, wield high power in the PFAS food packaging industry due to their ability to establish and enforce laws that directly impact all stakeholders. Their decisions shape the legal and operational frameworks for manufacturers, brand owners, and the chemical industry. Regulators also have a high interest in addressing PFAS issues, driven by their responsibility to protect public health and the environment. Their focus on reducing PFAS-related risks is reflected in initiatives like the EU-wide PFAS ban proposal under REACH, highlighting their commitment to enabling the transition to safer alternatives while balancing economic and societal impacts (PR1).

- NGOs focus on raising awareness about the harmful effects of PFAS on human health and the environment. They engage in public education campaigns, aiming to increase consumer awareness and put pressure on policymakers and industries to phase out PFAS use (NG).

Since they do not have formal regulatory authority, but can shape public perception and influence policymakers gives them moderate power. NGOs have a high interest in the issue of PFAS in food packaging because it aligns with their missions to protect public health, promote environmental sustainability, and reduce chemical pollution. Well-known NGOs are the Environmental Working Group, ChemSec and the Green Science Policy Institute.

- Academic institutions are key players in conducting scientific research, assessing the risks of PFAS, and developing safer alternatives. They provide data on PFAS toxicity, environmental persistence, and health effects, which is crucial for understanding the need for regulatory actions and for guiding the transition towards PFAS-free alternatives. Academic institutions hold moderate power in the PFAS food packaging system due to their influential role in providing scientific evidence and technical expertise but do not have direct influence on the decision-making. Since their main focus lays on creating academic value, instead of developing alternatives to specific PFAS products (AE). Therefore, they have moderate interest.

6 Functional Analysis Results

This chapter examines the systemic barriers hindering the adoption of PFAS-free alternatives in the food packaging industry. It focuses on five key areas: the willingness of manufacturers, customers, and brand owners to transition; the technical and innovation challenges of PFAS alternatives; financial obstacles; regulatory barriers; and the broader functional-structural dynamics within the system

6.1 Willingness To Change Among Manufacturers, Customers and Brand Owners

The transition to PFAS-free alternatives in the food packaging industry has been significantly influenced by the willingness to change among key stakeholders, namely manufacturers, customers, and brand owners. The varying degrees of readiness among these groups have presented challenges to achieving a complete transition.

6.1.1 Willingness to Change Among Manufacturers

Manufacturers play a critical role in driving the transition to PFAS-free alternatives. However, many manufacturers have been hesitant to adopt these changes. According to (NG), this reluctance can largely be attributed to a "business as usual" mindset prevalent across the industry. PFAS chemicals are highly effective and compliant with existing regulations, making them a convenient choice for manufacturers. Their favorable characteristics, such as grease and water resistance, make PFAS a valuable component in food packaging products. Without external triggers such as price incentives, regulatory restrictions, or reputational benefits, manufacturers are unlikely to prioritize transitioning to PFAS-free alternatives. The responsibility to develop viable alternatives rests primarily on manufacturers, yet many lack the chemical expertise to fully grasp the environmental and health risks associated with PFAS use (Schiavone and Portesi, 2023). This knowledge gap is compounded by a lack of urgency to transition, despite increasing awareness of these risks. Even in cases where sustainability departments within companies advocate for change, achieving approval from management often requires a deeper organizational understanding of the issue (NG). Furthermore, social and industrial acceptance of alternatives is often hindered by concerns over cost, performance, and reliability (Schiavone and Portesi, 2023).

6.1.2 Willingness to Change By Customers

The hesitancy of manufacturers to transition away from PFAS is exacerbated by a lack of demand from customers, particularly in sectors such as restaurants and cafes. These customers typically favor PFAS-containing products for their ability to maintain an ideal, grease-free appearance (NG, MF2). Many restaurant owners, who make critical purchasing decisions, are unaware of the presence of PFAS in the packaging they use. Their focus tends to be on replacing plastic with paper materials, without considering whether the paper is PFAS-free (MF1). This lack of awareness among customers diminishes the pressure on manufacturers to adopt PFAS-free alternatives, further delaying the transition.

6.1.3 Willingness to Change By Brand Owners

In contrast to the broader customer base, brand owners have generally shown greater willingness to phase out PFAS. These stakeholders are often more aligned with sustainability goals and view the transition as an opportunity to enhance the branding of their products. By adopting PFAS-free alternatives, brand owners can position themselves as environmentally responsible, which resonates positively with consumers. This proactive approach has allowed brand owners to take a leading role in driving innovation and setting industry trends (NG). This dichotomy creates a two-tiered market, with brand owners leading the way in adopting PFAS-free solutions, while other players remain hesitant. Ultimately, the push for PFAS-free alternatives is driven by end-consumers, pressure from the society or in response to regulatory pressures (NG).

6.1.4 Collaboration Among Stakeholders in the Transition to PFAS-Free Alternatives

The lack of willingness to change among certain stakeholders is compounded by insufficient collaboration across the food packaging industry (MF1). Despite the critical role that collaboration could play in driving the transition, current efforts remain fragmented and inconsistent. This fragmentation is evident in the limited interaction between competitors and the disconnect between stakeholders, such as manufacturers, researchers, NGOs, and regulatory bodies (PR1).

While some organizations, such as regulatory bodies and NGOs, have begun working closely with companies to promote safer alternatives, the industry-wide collaboration needed to align goals and share best practices remains inadequate. For example, NGOs often focus on raising awareness, while industries prioritize specific applications, leading to a mismatch in objectives. Competing priorities between large corporations with established resources and smaller companies with limited capacity further hinder unified progress (NG).

Additionally, some stakeholders are hesitant to collaborate due to concerns about competition or skepticism about the role of other groups(MF2). For instance, NGOs may have limited involvement in technical solution development, which is viewed as the responsibility of the industry and scientific community. This lack of structured collaboration undermines efforts to create systemic solutions, delaying the adoption of PFAS-free alternatives.

6.2 Functionality and Innovation Challenges of PFAS Alternatives

The second main barrier identified involves the technical challenges associated with transitioning to PFAS-free alternatives, particularly in terms of functionality and the innovation required to address these issues. Stakeholder perspectives reveal both optimism and skepticism about the feasibility and timeline of overcoming these barriers.

6.2.1 Innovation Challenges and Technical Barriers

A barrier lies in finding alternatives that meet the stringent performance requirements of PFAS-based materials, particularly in food packaging where durability and barrier properties are critical. According to regulatory stakeholders, the technical challenges often stem from the reliance on existing supply chain technologies, which lack incentives to explore alternatives until regulation or societal demand compels action (Brunn et al., 2023) (PR1, PR2). For example, the use of boron nitride as an alternative may reduce production speed, while other options introduce issues like unpleasant odors during processing, necessitating additional modifications to production facilities (PR2).

(MF2) argues that eliminating PFAS in packaging is technically straightforward, with available alternatives already on the market. However, others point to several factors that complicate the transition: lack of proper equipment for PFAS-free solutions, higher production costs due to additional material requirements, and confusion over regulatory definitions like those in the Single-Use Plastics Directive (MF3). Furthermore, the development and testing of alternatives require significant investment in research and collaboration with customers to meet specific performance expectations (MF3). Innovation is particularly needed in areas like polymer processing aids (PPAs) for plastic manufacturing. These technological advancements require more time to develop, and companies often request derogations to extend implementation timelines (PR2).

6.2.2 Performance of PFAS-Free Alternatives

Stakeholders recognize that PFAS-free alternatives generally do not perform as effectively as PFAS-based products in terms of grease and water resistance. However, this performance gap is narrowing, with many companies making significant improvements in their offerings (MF1). For example, while alternatives may provide slightly reduced functionality, such as pizza boxes that remain waterproof for one and a half hours instead of two, this reduction is often inconsequential for practical applications (PR2, MF2).

There is growing consensus that many PFAS-based products are over-engineered, offering higher performance than necessary. Industries must shift their mindset to focus on the specific functionality required for an application rather than striving for unnecessarily high standards (NG). This could reduce the perceived performance gap between PFAS and non-PFAS materials (Simona A Bălan; Thomas A Bruton; Kimberly G Hazard, 2023). Additionally, alternatives generally provide fixed levels of performance, unlike PFAS, which allows for customized coatings with varying levels of grease resistance. While this reduces flexibility, the alternatives still meet the needs of many applications (Trier et al., 2018) (MF3).

6.2.3 Regrettable Substitution

Stakeholders express concerns about the risk of regrettable substitution, replacing PFAS with alternatives that introduce new risks to human health or the environment (AE, NG). Companies must conduct thorough chemical safety evaluations and alternative assessments to mitigate this. However, limited information on the toxicity, bioaccumulation, and persistence of many alternative materials makes it challenging to ensure their safety and sustainability (Zabaleta et al., 2020). Most data for alternatives are derived from small-scale tests and are not standardized, complicating their direct comparison with PFAS or each other (Simona A Bălan; Thomas A Bruton; Kimberly G Hazard, 2023). Tools for identifying chemical hazards and understanding toxicological endpoints have improved, but continuous research is essential to ensure that substitutes do not replicate the issues associated with PFAS (NG).

6.2.4 Divergent Views on Innovation

There are divergent views on the difficulty of changing to PFAS-free alternatives. According to (AE), PFAS-free alternatives are already widely used, and manufacturers should not face significant difficulties in finding effective substitutes or adapting their production processes. This is because manufacturers are accustomed to regularly modifying their processes to meet changing demands, making such transitions a standard part of their operations (AE, PR1). Although this argument is not refuted by any other stakeholder, multiple stakeholders emphasize that scaling up PFAS-free alternatives remains a significant obstacle (PR2, MF1, MF2, MF3). European companies, for instance, are still building capacity and infrastructure for new materials, which complicates the transition (MF1) .

In summary, while technical challenges and performance gaps remain, there is optimism that innovation and collaboration can overcome these barriers. Stakeholders highlight the importance of adjusting expectations, improving chemical safety evaluations, and building the necessary infrastructure to support a successful transition to PFAS-free materials.

6.3 Financial Hurdles in Transitioning to PFAS-Free Alternatives

The third main barrier identified is the financial burden of transitioning to PFAS-free alternatives in the food packaging industry. The financial burden as a barrier is a topic of diverse perspectives among stakeholders, with opinions ranging from skepticism about the long-term impact to highlighting significant upfront challenges.

According to academic experts, while the initial transition to PFAS-free alternatives may require substantial investments to adapt processes and technologies, the financial challenge is not insurmountable (AE). PFAS itself is not inexpensive, and once new production processes are established, economies of scale can make these alternatives economically viable in the long term (AE).

This view emphasizes that financial hurdles are temporary and can be mitigated as the market matures. According to the report of OECD (2020), non-fluorinated alternatives increase the price of food packaging by approximately 11-32% compared to PFAS-based materials.

6.3.1 Financial Pressure and Regulatory Anticipation

The NGO highlights the immediate financial pressures companies face due to the anticipation of regulatory changes. The need for innovation and new processes often involves a big investment, which can strain companies unprepared for such transitions. However, brand owners are more likely to invest early, viewing this as an opportunity to enhance their sustainability image and differentiate themselves in the market (NG).

6.3.2 Comparisons and Scaling Challenges

From the perspective of manufacturers, the cost of PFAS-free alternatives presents a bigger challenge. PFAS benefits from large-scale production, making it cheaper than newer, more sustainable materials produced at smaller scales. This price gap creates a financial barrier for many companies, especially those without the resources to absorb the increased costs of alternatives (MF1) [F6]. For larger brands such as McDonald's, the switch to PFAS-free packaging has been feasible despite higher costs. However, smaller companies, particularly those operating in low-margin contexts such as festivals, often prioritize cheaper products, even if they contain PFAS (MF2).

6.3.3 Phases of Financial Investment

Transitioning to PFAS-free alternatives involves three critical phases, each contributing to the financial hurdle:

1. Development of substitute materials: While some alternatives have already been developed, this process requires significant research and innovation.

2. Certification for food applications: Alternatives that come into direct contact with food must meet stringent safety standards. Securing certifications typically costs hundreds of thousands of euros and takes 12 to 18 months.

3. Scaling up production: Beyond developing and certifying alternatives, companies must invest in scaling production and potentially modifying existing machinery to accommodate new materials (MF2).

Despite these challenges, manufacturers note that once these phases are completed, PFAS-free alternatives may not be inherently more expensive than PFAS-based materials when produced at scale (MF2). While some stakeholders, like academic experts, view financial challenges as manageable in the long term, others highlight the significant short-term hurdles that can impede smaller companies and those unprepared for the shift.

6.4 Regulation as a Barrier to PFAS-Free Alternatives

The fourth barrier is the current absense of strict regulations. A major challenge lies in the lack of harmonized regulations across countries. As highlighted by Zabaleta et al. (2020), inconsistent enforcement of PFAS-related regulations within Europe has created market fragmentation. Without unified standards for testing and limit values, industries face uncertainties that hinder the adoption of alternatives. Denmark's early action in banning PFAS in paper and board food packaging in July 2020 exemplifies the potential of stringent regulations. Research from Strakova et al. (2021) revealed that McDonald's in Denmark replaced PFAS-treated packaging, while similar products in the Czech Republic and the United Kingdom still contained PFAS. This disparity underscores the importance of EU-wide harmonization to ensure consistent protections for consumers across countries.

6.4.1 Harmonization in Food Packaging Regulation

The absence of strict regulation fails to motivate industries to move away from PFAS-containing products. For smaller businesses, such as cafes and restaurants, legislation often becomes the sole driver compelling them to transition. According to (AE), the lack of regulatory pressure creates inertia, while inconsistent national approaches allow companies to exploit loopholes, delaying meaningful changes. In many cases, unclear definitions within existing regulations exacerbate these delays. For example, (MF2) noted that regulations like the Single-Use Plastics Directive in the Netherlands classify many PFAS-free alternatives as plastics, preventing their use in disposable products despite their environmental benefits. This regulatory paradox inadvertently supports the continued use of PFAS-containing materials, even as they pose environmental risks.

Uncertainty around regulatory timelines and criteria further discourages innovation. Companies often hesitate to invest in research and development for PFAS-free materials without clear and enforceable standards. As highlighted by (NG), regulatory uncertainty impedes progress, leaving industries reliant on existing PFAS-based solutions. This challenge is compounded by the complexity of direct food contact approvals, which require significant time and investment. An example provided by (MF4) illustrates this difficulty: their transition to compliant food packaging was delayed by five to six years due to stringent certification requirements. However, with investments in safer adhesives and upgraded facilities, they eventually overcame this hurdle.

6.4.2 Harmonization in the REACH Proposal

The introduction of a comprehensive PFAS ban is expected to drive significant changes in the market. As noted in the findings of Strakova et al. (2021), clear timelines and strict enforcement can help ensure that manufacturers prioritize PFAS-free alternatives. However, inconsistencies in implementation may undermine this progress. The experience in Denmark demonstrates that strong regulation can effectively eliminate PFAS from food packaging, but its success depends on consistent enforcement across the European Union. Without harmonized rules, manufacturers face a fragmented market that discourages the widespread adoption of alternatives.

The proposed PFAS ban has also raised questions about international compliance. Many disposable food packaging products are manufactured in low-wage countries, such as China, where regulatory standards may not align with EU requirements. This discrepancy creates additional enforcement challenges. Stricter border controls and monitoring are essential to ensure that imported products comply with European regulations. Lessons from the U.S. suggest that giving manufacturers sufficient time to transition is critical to avoiding disruptions. However, proposals in the packaging sector often become diluted during implementation, with extended timelines and lenient requirements undermining their effectiveness.

The issue of derogations further complicates regulatory efforts. According to (PR2), companies may request extensions to continue using PFAS, citing challenges in implementing alternatives. While derogations can provide flexibility for industries genuinely struggling to transition, they must be granted based on well-substantiated evidence of ongoing efforts to find alternatives. A two-tiered system, with a 5-year extension for available alternatives requiring additional time for implementation and a 12-year extension for cases where no alternatives exist, ensures that only necessary exemptions are granted (ECHA, 2023). However, regulators must carefully monitor progress to prevent misuse of these extensions and ensure that lagging companies do not gain an unfair advantage over proactive competitors.

Determining essential use remains another regulatory challenge. Historically, this responsibility has fallen to regulators, who often lack the expertise and resources to make these decisions. According to Karinen et al. (2024), the burden of proof should shift to the industry, requiring companies to demonstrate that their PFAS use is essential and that no safer alternatives exist. This approach would align incentives for manufacturers to invest in innovation and accelerate the transition.

6.4.3 ECHA's perspective on banning PFAS in food packaging products

The ECHA is responsible for defining which products fall into specific categories under the concept of essential use. The ECHA concluded that all PFAS containing products in the food packaging industry must be replaced. The reasoning of the ECHA is divided into cost and availability arguments to ban all PFAS in the food packaging industry.

Financial consequences of removing PFAS ECHA concludes that PFAS-free alternatives are cost-comparable to PFAS-based food packaging products in most cases. The ECHA based evidence on the report of (Washington State Department of Ecology Olympia, 2021), which demonstrates that switching to non-fluorinated options typically results in only marginal cost differences, which do not exceed 10% in most scenarios. The marginal cost increase is not significant enough to justify continued use of PFAS, especially when considering the environmental and health benefits of substitution. Furthermore, the Annex states that the cost implications for manufacturers are manageable, particularly when considering long-term savings in waste management and health-related costs. PFAS-free alternatives do not impose excessive financial burdens on manufacturers or end-users (e.g., restaurants or fast-food chains), reinforcing their economic feasibility.As last, the Annex highlights that multiple manufacturers are already producing PFAS-free food packaging at a commercial scale. This indicates the market has matured sufficiently to support a broad transition. The availability ensures that financial risks related to supply shortages are mitigated.

Technical challenges in producing PFAS-free alternatives PFAS-free alternatives have been shown to provide sufficient functionality for most food packaging applications, including essential properties such as grease-proofing and water resistance. While these alternatives may exhibit slightly lower performance under extreme conditions, such as prolonged exposure to high levels of grease or during extended storage durations, they generally meet the core requirements for food safety and usability. The ECHA determined that the technical performance gap is not substantial enough to prevent the substitution of PFAS, particularly given ongoing advancements in alternative materials. Furthermore, a wide range of non-fluorinated alternatives is already in use, including coatings made from waxes, polymers, or bio-based materials, which have proven successful in applications like disposable tableware and fast-food packaging. The diversity of these alternatives demonstrates that technical barriers to substitution are minimal. The Annex further highlights that while certain niche applications may require continued research and development, most food packaging applications already have effective PFAS-free solutions. Moreover, ongoing innovation in alternative materials continues to close any remaining gaps, ensuring a viable pathway for the full replacement of PFAS. The ECHA also acknowledges the potential risk of regrettable substitution, where PFAS might be replaced by other substances with harmful environmental or health impacts. To address this, the Annex incorporates mechanisms to ensure that alternatives meet stringent safety and sustainability standards, thereby reducing the likelihood of unintended consequences.

6.4.4 Illustrating the Challenges of Effective Regulation

Although the consultation round conducted by the ECHA received limited responses from the food packaging industry not involving fluoropolymers (N=6), the submitted reactions highlighted a significant case illustrating the complexities of regulating PFAS. These complexities particularly concern the challenges and unintended consequences that can arise from implementing a full ban on PFAS-containing substances. This case study focuses on the flexible packaging industry, which, while striving to align with EU regulations under the Packaging and Packaging Waste Regulation (PPWR), encounters unique obstacles related to the use and recycling of PFAS-containing materials. It sheds light on the intertwined challenges of transitioning to PFAS-free alternatives and maintaining compliance with evolving regulatory demands.

Flexible Packaging Europe is the industry association representing the interests of more than 85 small, medium-sized and multinational manufacturers of flexible packaging. The flexible packaging industry increasingly uses mono-materials like mono-PE (polyethylene), mono-PP (polypropylene), and mono-paper to meet EU regulations under the Packaging and Packaging Waste Regulation (PPWR), which emphasize recyclability and increased recycled content. However, the production of these thin, flexible films often relies on fluoropolymer-containing processing aids, and they may be coated or printed with PTFE-containing inks or lacquers.Even as alternatives to these PFAS-containing aids and coatings become available, existing PFAS-containing packaging materials are entering the recycling stream. These fluoropolymers and short-chain PFAS compounds are not effectively removed during recycling, resulting in recycled materials containing PFAS. Moreover, because recycled materials are derived from mixed and untraceable waste sources, their precise composition is often unknown, making it difficult to ensure compliance with proposed limits for PFAS content (e.g., 25 ppb for individual PFAS). The problem is exacerbated by the closed-loop nature of recycling, where PFAS from virgin materials persist in the recycling system. The PFAS content in recycled materials can only decrease if virgin PFAS-containing materials are phased out for a long enough period to eliminate their presence in the recycling loop.

6.5 Functional-structural analysis of the barriers

In this subsection, the identified barriers are analyzed through the functional analysis of the seven key system functions and their structural components to uncover the underlying systemic problems..

6.5.1 TIS development via knowledge development

The TIS for transitioning to PFAS-free alternatives in the food packaging industry starts with the foundational role of knowledge development. This TIS was initiated by academic research into the toxicological effects of PFAS and collaboration among organizations studying how PFAS in food packaging contributes to human bioaccumulation. These findings raised awareness about the health and environmental risks posed by PFAS, creating the impetus for innovation toward PFAS-free alternatives. This research not only raised awareness but also led to early regulatory actions. Certain states in the USA, such as Maine and Washington, and Denmark were among the first to implement regulations targeting PFAS in the food packaging industry, before the ECHA proposed a full-ban on PFAS (ECHA, 2023)(Strakova et al., 2021).

6.5.2 Attraction of entrepreneurs

When more general knowledge on the hazards of PFAS in products is developed, it is the role of the entrepreneurs to develop sector-specific innovations to transition to pfas free alternatives. The heightened awareness of PFAS toxicity motivated entrepreneurs to develop PFAS-free alternatives. However, these activities lagged in the early stages due to a lack of direct incentives for innovation. Manufacturers, as the primary entrepreneurs in the food packaging industry, were largely resistant to change unless compelled by regulations. PFAS was a highly functional and established material, and without significant consumer or market pressure, many companies did not prioritize innovation. It was only after rapid regulatory advancements, including the proposed EU PFAS ban, that entrepreneurs began accelerating their efforts to transition toward PFAS-free solutions. Unlike other TIS contexts that require the development of entirely new technologies, the food packaging industry already has well-established manufacturers that must adapt their existing processes and products. However, the transition is complicated by the sector-specific nature of PFAS usage, as removing PFAS from certain products requires tailored solutions.

6.5.3 Knowledge dissemination

Although NGOs, regulators, and academia actively engaged in diffusing knowledge about PFAS-free alternatives, there was limited interest from the industry in participating in these networks. For the industry, the scope of knowledge development remained narrowly focused, as companies primarily concentrated on manufacturing specific products using particular PFAS compounds and exploring specialized alternatives tailored to their production lines. This situation created uncertainty about whether such investments would yield significant returns.

The development of alternatives required extensive and highly specific data, which was difficult to obtain due to the complexity of the numerous variables involved (Brunn et al., 2023). This significant data gap further discouraged entrepreneurs from participating in collaborative networks. The highly specialized nature of the knowledge needed to develop and implement alternatives made it less appealing for entrepreneurs to engage in collaborations with stakeholders of the NGO's, academia and other industries.

6.5.4 Guidence of the search

An important indicator of the guidance of the search in this TIS was the growing body of knowledge on the toxicity of PFAS. While there were consumers willing to pay a premium for compostable products, the highly competitive nature of the food packaging industry—dominated by inexpensive, widely available products—tempered expectations for a strong focus on PFAS-free alternatives. However, the guidance of the search has gained significant momentum following the ECHA proposal to ban PFAS in food packaging.

With the impending restriction on PFAS use, the prospects for companies offering PFAS-free alternatives have become increasingly promising. This shift began earlier in regions like Denmark and certain U.S. states, where restrictions on PFAS use created a foundation for change. However, the recent regulatory developments have heightened the urgency for companies to actively invest in R&D and adapt their products to incorporate PFAS-free alternatives.

6.5.5 Market formation

Market formation for PFAS-free alternatives in the food packaging industry is at an early stage, characterized by both promising developments and persistent barriers. While rising consumer demand for sustainable and compostable packaging has created a favorable environment for innovation, this demand is largely concentrated among environmentally conscious segments. Early inertia in market formation slowed the widespread adoption of safer solutions, as the transition to alternatives required navigating complex variables, including the diversity of PFAS compounds, food packaging products, and available substitutes. Despite these challenges, the economic feasibility of PFAS-free alternatives is evident. For example, a major distributor in the United States successfully transitioned to PFAS-free packaging without incurring additional costs, demonstrating that such changes can be financially viable. Moreover, the functional limitations of these alternatives have proven to be relatively minor, neither significantly increasing costs nor compromising utility. However, financial barriers still constrain the scaling of alternatives, particularly for smaller companies with limited resources.

6.5.6 Resource mobilization

The transition to PFAS-free alternatives requires specialized expertise in material science and food safety to develop effective solutions. However, limited collaboration and knowledge sharing among stakeholders, including NGOs, academia, and industry, have impeded the optimal use of existing expertise. This challenge is further exacerbated by the high level of specialization required, which discourages widespread participation from the industry.

Developing and scaling these alternatives also demands significant financial resources for R&D, pilot projects, and market introduction. Despite this need, financial incentives such as subsidies, which could accelerate innovation and adoption, are notably absent in the food packaging sector. Companies face substantial uncertainty about the cost-effectiveness and scalability of alternatives, making them reluctant to invest without more robust regulatory frameworks or market-driven incentives.

Nevertheless, the availability of alternative materials does not appear to be a bottleneck, as there is a sufficient supply of materials capable of replacing PFAS in food packaging applications (PR1)(PR2)(NG).

6.5.7 Creation of legitimacy and counteracting resistance to change

Companies with significant investments in PFAS-based products face economic disincentives to transition, driven by sunk costs in existing technologies and production lines. Denmark successfully implemented bans on PFAS in packaging, but in other countries, resistance from stakeholders within PFAS-reliant industries has slowed broader adoption. NGOs and academic institutions have played a pivotal role in raising awareness about the harmful effects of PFAS, generating public pressure for regulatory changes. However, the complexity of transitioning to PFAS alternatives has made it challenging to coordinate lobbying efforts across specialized industries, as each faces unique variables and requirements. This complexity has also hindered the harmonization of regulations on PFAS alternatives. With the introduction of consistent regulations, such as the proposed ban, there is now greater potential to strengthen legitimacy and drive alignment across regions.

6.6 Systemic problems summarized

From the results section based on the analysis of the TIS functions, the following systemic problems are derived, based on thei nnovation policy framework of figure 5 .

1. Actor's problems:
    - Manufacturers lack the ability or willingness to innovate (F1: entrepreneurial activities)
    - Manufacturers fail to utilize available resources effectively (F2: knowledge development).
2. Institutional problems:
    - Absence of clear incentives to phase out PFAS for manufacturers (F4: guidance of the search)
    - Lack of harmonized regulations across the EU (F4: guidance of the search),
    - Regulatory ambiguities that hinder transitions, such as in classification conflicts in the single-use plastics directive (F6: resource mobilization)
3. Interaction problems:
    - Weak coordination between researchers, manufacturers, and NGOs, resulting in isolated efforts and limited knowledge sharing.(F3: knowledge dissemination)
    - Mismatched goals between stakeholders (e.g., industries focus on cost and performance while NGOs emphasize environmental risks), leading to misaligned priorities (F7: Legitimacy Creation).
4. Infrastructural problems: No significant infrastructural issues were identified as systemic problems in this TIS.

A graphical representation of the systemic problems is displayed in figure 9, in which the lines show the weak links in between the functions of the TIS and the structural components of the TIS. The different colours are used for visibility reasons.

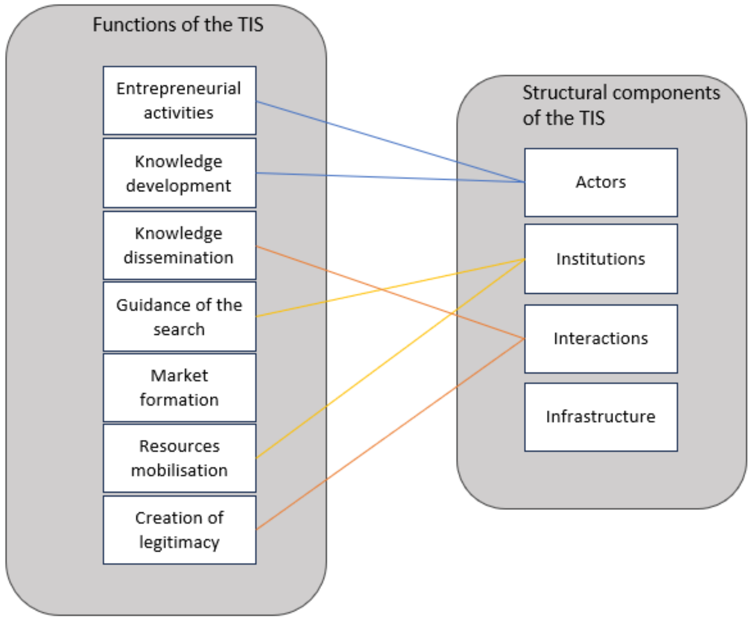

Figure 9: Systemic problems of TIS in the transition to PFAS free alternative in the food packaging industry

7 Strategies to overcome systemic problems

This chapter outlines the strategies proposed in the literature and interviews to address the barriers in transitioning to PFAS-free alternatives in the food packaging industry. Following the presentation of these strategies, their alignment with the objectives of systemic instruments designed to tackle systemic problems will be evaluated.

7.1 Regulatory Strategies

The following key regulatory strategies are proposed to facilitate the transition to PFAS-free alternatives in the food packaging industry. At first, (PR1) emphasized the need for clear, science-based regulations that set realistic timelines for implementation. This approach would ensure that companies have sufficient time to transition while maintaining public health protections. (MF1) argued that enforceable regulations with specific deadlines would naturally compel the industry to innovate, making financial incentives unnecessary. With the ECHA's proposal for the ban, science-based regulations with a clear timeline have been established as the annex provides clear guidance on the definition, scope, substitutability, compliance thresholds, timelines, evidence for alternatives, derogation processes, monitoring mechanisms, and safety criteria for substitutes (ECHA, 2023). These aspects offer manufacturers, regulators, and other stakeholders a structured framework for transitioning away from PFAS while ensuring regulatory alignment and environmental protection. All stakeholders had the opportunity to challenge these regulations, and for those who chose not to, that opportunity has now passed. It is now the responsibility of member statesstra to enforce and adhere to this ban (AE). Furthermore, government subsidies for pre-competitive research were suggested by (AE) as a means to accelerate early innovation. These subsidies should gradually taper off as companies take responsibility for scaling up viable solutions. The book of Simona A Bălan; Thomas A Bruton; Kimberly G Hazard (2023) adds to this to provide financial incentives or subsidies for manufacturers to invest in new infrastructure and processes needed for producing PFAS-free alternatives. On the other side, (MF1) argued that subsidies might add unnecessary complexity and that regulatory certainty alone could prompt companies to invest in innovation and transition to alternatives. At last, when industries request derogation periods, (PR2) stressed that such requests must be well-substantiated. A 5-year extension could be granted when alternatives exist but require more time for implementation, while a 12-year extension could apply to cases needing further research. The example of thin films discussed in section (6.4.4) serves as a strong illustration that, with well-founded argumentation, a derogation period can be granted in cases of exceptional circumstances. However, derogations would not be granted to lagging companies if a significant portion of the market had already transitioned (PR2).

7.2 Collaboration and Stakeholder Engagement

Collaboration among stakeholders is essential to overcoming both technical and systemic barriers in the transition to PFAS-free materials, yet the current partnerships between industry, regulators, and NGOs are limited in scope and effectiveness. (PR1) and (PR2) emphasized the need for enhanced cross-sector collaboration to align goals and share best practices. This can be in the form of workshops and grants, as suggested by (NG), to foster collaboration and encourage the development of alternatives. Furthermore, successful initiatives, such as the ChemSec marketplace, illustrate the potential of collaboration. This platform connects supply and demand for safer alternatives by bringing together companies, regulators, and NGOs to promote toxic-free solutions. It highlights how coordinated efforts can strengthen trust in alternatives and drive their adoption. Strengthening and expanding such initiatives could address the fragmentation currently impeding progress.Moreover, partnerships between larger corporations with robust R&D capabilities and smaller companies with greater flexibility can foster innovation. Larger companies can offer resources, while smaller firms can contribute agility and a willingness to experiment. This symbiotic relationship could help overcome the technical challenges associated with PFAS-free alternatives (NG). A third collaboration strategy is to create consumer awareness campaigns promoting the benefits of sustainable materials. These were recommended by (PR1) and (MF1) as a means to drive demand for PFAS-free products. Educating consumers about PFAS risks and encouraging acceptance of minor product imperfections, such as grease stains, could accelerate the transition, since it prevents over-engineering (MF2) (Strakova et al., 2021). (NG) and (MF2) noted that focusing on the specific functionality required for each application could reduce the perceived performance gap between PFAS and non-PFAS materials. Other awareness campaigns that are suggested are for fast-food chains and food retailers to display their commitment towards moving away from hazardous chemicals by joining the ‘No to PFAS’ corporate movement organised by ChemSec, to publicly report on progress and announce when their food contact materials are PFAS-free (Strakova et al., 2021). This encourage industry leaders to earlier transition, since it creates a competitive and ethical advantage (Glenn et al., 2021)(Trier et al., 2018).

7.3 Synthesis of the results section

The synthesis of the functional-structural analysis and the systemic instrument goals is briefly summarized in figure 10. The systemic instrument goals for the TIS are based on the theoretical framework established by Wieczorek and Hekkert (2012). The theoretical systemic instrument goals outlined in their work are illustrated in figure 5. This analysis reveals no systemic instrument goals aimed at enabling manufacturers to utilize available resources effectively. To address this systemic problem, entrepreneurial activity must originate from the manufacturers themselves. They need to demonstrate initiative and entrepreneurship, as the necessary resources are already available and can be effectively applied.

Systemic problems	Systemic instrument goals
Actor's problems	
Manufacturers lack the ability or willingness to innovate (F1: entrepreneurial activities)	Collaboration initiatives and regulatory pressure
Manufacturers fail to utilize available resources effectively (F2: knowledge development)	
Institutional problems	
Absence of clear incentives to phase out PFAS for manufacturers (F4: guidance of the search)	Regulatory pressure of the ECHA
Lack of harmonized regulations across the EU (F4: guidance of the search)	Proposed ban of the ECHA
Regulatory ambiguities that hinder transitions (F6: resource mobilization)	Regulatory harminozation
Interaction problems	
Weak coordination between researchers, manufacturers, and NGOs (F3: knowledge dissemination)	Collaboration initiatives
Mismatched goals between stakeholders leading to misaligned priorities (F7: Legitimacy creation)	Collaboration initiatives

Figure 10: Systemic instrument goals aimed at addressing the systemic problems of the TIS

8 Discussion

This research investigated the challenges associated with transitioning to PFAS-free alternatives in the food packaging industry using the TIS framework. The study aimed to identify the systemic barriers that hinder the adoption of PFAS-free solutions and propose strategies to address these issues. A functional-structural analysis was conducted to examine the roles of key actors, institutions, networks, and infrastructure within the innovation system. The research was based on a combination of literature review, analysis of regulatory documents and stakeholder responses to the proposed PFAS ban, and semi-structured interviews with key stakeholders, including manufacturers, brand owners, regulatory bodies, and NGOs. The interview questions were developed based on the seven functions of the TIS framework to accurately capture the dynamics of the TIS in the transition to PFAS-free alternatives within the food packaging industry. This multi-method approach provided a comprehensive understanding of the systemic problems and the underlying dynamics within the system.

When positioning the findings of this research to existing studies, it provides an update of the system in the transition to PFAS-free alternatives in the food packaging industry. This was achieved due to the multi-faceted nature of the study, which examined the Annex of the ECHA's proposal for the ban, analyzed stakeholder reactions to the Annex, and included interviews with key stakeholders. These interviews allowed for the identification of barriers in the transition to PFAS-free alternatives and strategies to address these barriers, following the implementation of the proposal.

8.1 Practical relevance

In existing literature, high concerns were raised regarding the feasibility of transitioning to PFAS-free alternatives in food packaging. By examining the Annex of the ECHA's proposal for the PFAS ban and analyzing the formal responses submitted during the consultation phase, this study explored the full system of PFAS-free alternatives after the proposal was implemented. Interestingly, the proposal received very few formal reactions from stakeholders specifically within the food packaging sector. This limited response suggests a broad consensus among industry actors, policymakers, and other stakeholders regarding the urgency to phase out PFAS in this industry. The lack of significant opposition underscores a shared acknowledgment of the environmental and health risks posed by PFAS, as well as the availability of feasible alternatives for most applications. This finding validates the research of (ECHA, 2023), which confirms that alternatives are indeed available to replace PFAS in the food packaging industry and that the innovation system does not present insurmountable technical challenges for achieving this transition. Furthermore, this research builds on the findings of Cousins et al. (2019), who introduced the essential use framework as a method for categorizing PFAS. This study demonstrates that the essential use concept is an effective approach for identifying PFAS applications that can and should be replaced. The article by Strakova et al. (2021) identified the persistence of PFAS in food packaging and proposed regulatory and collaborative strategies for transitioning to PFAS-free alternatives. This study utilized these strategies and expanded upon them by incorporating updated strategies provided by the stakeholders interviewed in this research. Additionally, this study builds on the OECD report (OECD, 2020), which examined market conditions and strategies for reducing PFAS use. By providing an updated analysis, this research contributes new insights into the market penetration of alternatives and identifies current barriers to scaling up production. Through the lens of the TIS framework, this study illustrates that while systemic problems persist, such as financial burdens for smaller manufacturers and gaps in collaboration among stakeholders, the system still shows significant potential for progress. The practical relevance of this study can be summarized with a positive insight, as the results indicate that nearly all systemic problems can be addressed through the effective implementation of the comprehensive PFAS ban in the food packaging industry, combined with collaborative efforts from key stakeholders. These are feasible and realistic measures to guide the food packaging industry toward PFAS-free alternatives with the current obstacles.

8.2 Theoretical relevance

This study has provided a valuable contribution to the literature by applying the TIS framework to the transition toward PFAS-free alternatives in the food packaging industry. While the TIS framework has been successfully applied in energy and mobility transitions, its use in the food packaging sector, particularly for chemical substitution systems, highlights unique aspects of the current transition and raises important theoretical considerations.The findings reveal that the PFAS-free transition operates less as a traditional innovation system and more as a chemical substitution system. While an innovation system typically involves radical technological development driven by market and regulatory forces (Hekkert et al., 2007), a chemical substitution system focuses on identifying and implementing safer alternatives to existing substances with similar performance. This identified unusual key characteristics for applying a TIS. Unlike generalized technologies, the PFAS-free alternatives are highly product-specific, as each application in food packaging (e.g., pizza boxes, microwave popcorn bags) has unique performance requirements and challenges. This level of granularity complicates systemic innovation. Furthermore, the substitution process does not typically involve disruptive innovation but rather incremental changes in chemical formulations and production processes. Despite the PFAS transition being closer to a chemical substitution system, the TIS framework resulted in valuable insights because of its ability to identify and categorize systemic barriers, and connect these systemic barriers with targeted policies.

8.3 Limitation on the TIS

While the TIS framework proved valuable in this study, it also has certain limitations in this defined system.

In a typical TIS, the innovation process often spans across multiple sectors, enabling broad applicability of technological advancements (Tziva et al., 2020). For instance, renewable energy technologies such as solar panels or wind turbines have applications across energy generation, infrastructure, and even consumer products (Trencher et al., 2022). This breadth allows for economies of scale and cross-sectoral learning, accelerating the pace of innovation and adoption. In contrast, the innovation process for PFAS-free alternatives in food packaging is highly specialized, focusing on chemical properties tailored to specific products and use cases. Each application requires alternatives that replicate the unique characteristics of PFAS—such as water and oil resistance—under varying conditions. For example, a substitute suitable for microwave popcorn bags may not meet the requirements for fast-food containers. This specialization makes the development process resource-intensive and fragmented, as each use case requires unique R&D investments. Consequently, innovation efforts are less scalable and often siloed, impeding collective progress. Furthermore, the narrow specialization limits the potential for generalizable breakthroughs. Unlike broader technological innovations, which can benefit from cumulative learning across applications (Andersen and Gulbrandsen, 2020), PFAS-free alternatives rely on case-specific advances. This adds to the complexity and slows the innovation cycle, particularly when resources and expertise are limited.

Furthermore, collaboration is a hallmark of successful TIS development in many sectors, as it fosters knowledge sharing, reduces duplication of efforts, and aligns stakeholders toward common goals (Tziva et al., 2020). In traditional TIS examples like the energy sector, strong networks between industry players, academia, and policymakers play a critical role in advancing innovation and adoption (Andersen and Gulbrandsen, 2020). However, in the PFAS substitution TIS, industry collaboration has been limited. Companies often work independently to develop alternatives tailored to their specific production lines. This is driven by the competitive nature of the food packaging industry, where proprietary technologies and intellectual property are critical for maintaining market advantage. As a result, knowledge sharing is minimal, and the diffusion of successful solutions across the industry is constrained. Additionally, the complexity of PFAS substitution creates further barriers to collaboration. The industry must navigate diverse variables, including the chemical composition of PFAS compounds, the technical requirements of food packaging products, and the varying functionalities of potential alternatives. This complexity discourages companies from pooling resources or engaging in joint ventures, as the outcomes may not directly benefit their specific needs. The lack of collaborative platforms exacerbates the fragmentation of innovation efforts, leaving smaller companies particularly disadvantaged due to limited access to knowledge and resources.

As last, in many standard TIS examples, market forces play a central role in driving innovation and adoption. Consumer demand, competitive pressures, and financial incentives often create a fertile environment for technological advancements (Tziva et al., 2020). For instance, in the renewable energy sector, market mechanisms such as feed-in tariffs, carbon pricing, and green consumer preferences have been pivotal in shaping the TIS (Trencher et al., 2022). In the case of PFAS substitution, however, the primary driver of change is regulation rather than market forces. The ECHA proposed ban on PFAS in food packaging is a clear example of regulatory intervention creating the impetus for innovation. While regulations are essential for addressing the environmental and health impacts of PFAS, their predominance in the TIS highlights the absence of strong market-driven incentives.

The lack of subsidies, tax incentives, or other financial support mechanisms for PFAS-free alternatives has further limited market formation. Companies face significant uncertainty about the cost-effectiveness and scalability of alternatives, leading to hesitancy in making proactive investments. Consumer demand for sustainable packaging has begun to emerge, but it is insufficient to offset the dominance of regulatory pressures in guiding the TIS.

The reliance on regulation also introduces challenges related to harmonization. Different countries and regions have varying timelines, standards, and enforcement mechanisms for PFAS restrictions, creating fragmentation and uncertainty in the market. While regulatory frameworks like the ECHA proposal aim to provide consistency, the historical lack of alignment has delayed progress in developing and adopting alternatives.

9 Conclusion

The thesis examines the main research question:

What are the key challenges for implementing PFAS-free alternatives in the food packaging & food contact materials industry?

The findings of this research highlight that the transition to PFAS-free alternatives in the food packaging industry faces several key challenges, many of which are systemic in nature. These challenges arise from technical, economic, and regulatory barriers, as well as the need for stronger collaboration among stakeholders. However, the research also reveals that these challenges are not insurmountable and that significant progress can be made through a combination of regulatory implementation and collaborative strategies.

One of the primary challenges is the complexity of replacing PFAS across diverse food packaging products. Even within the food packaging industry, PFAS applications are highly product-dependent, meaning that no single alternative can replace PFAS universally. This product variability requires tailored solutions, which complicates the scaling and market introduction of PFAS-free alternatives. For niche applications, technical barriers remain significant, as alternatives often lack the specific performance qualities that PFAS provide, such as water and grease resistance.

Economic barriers further constrain the transition. Smaller manufacturers, in particular, face financial pressures as they lack the resources to invest in research, testing, and certification of alternatives. These economic hurdles are exacerbated by the lack of clear financial incentives, which are crucial for smaller stakeholders to scale up PFAS-free solutions. Larger companies, on the other hand, have demonstrated progress due to their greater capacity for research and development, but they, too, face challenges in achieving widespread adoption.

Regulatory frameworks play a dual role as both a driver and a barrier. The proposed PFAS ban by the ECHA provides a clear regulatory push for the phase-out of PFAS in food packaging, with its annex offering science-based guidance on alternatives and compliance thresholds. While the annex identifies viable alternatives for many PFAS applications, concerns were raised about the feasibility of replacing PFAS in all products within the proposed timelines, particularly for niche markets. Stakeholders emphasized the importance of derogations for exceptional cases where alternatives are not yet fully developed or scalable.

From a systemic perspective, this study identified several systemic problems that hinder the transition. These include weak knowledge sharing among stakeholders, financial barriers to innovation, and limited collaboration between regulators, manufacturers, and NGOs. Despite these challenges, the results demonstrate that the PFAS ban, if properly implemented, can address many of these systemic problems. Regulatory certainty encourages market formation, drives innovation, and compels industry actors to align their goals with the transition to PFAS-free alternatives. In parallel, collaborative efforts—such as government subsidies, pre-competitive research funding, and educational campaigns—are needed to overcome systemic barriers and ensure stakeholder alignment.

A key finding of this research is the relatively limited resistance to the proposed PFAS ban from stakeholders in the food packaging industry. The lack of significant opposition during the consultation phase suggests broad agreement on the urgency to phase out PFAS, coupled with confidence in the availability of alternatives. This is a critical insight, as it indicates that the perceived challenges are manageable with the right regulatory, economic, and collaborative measures in place.

In conclusion, this study underscores that the challenges in transitioning to PFAS-free alternatives, while substantial, can be addressed through a combination of regulatory enforcement, stakeholder collaboration, and targeted financial and technical support. The proposed PFAS ban serves as a foundational instrument for driving this transition, while collaborative strategies and entrepreneurial initiatives will ensure that systemic problems are resolved. By aligning regulatory frameworks with practical implementation strategies, the food packaging industry can achieve a sustainable shift toward PFAS-free solutions without significant disruption. This study contributes a critical update to the literature, validating the feasibility of alternatives and providing a pathway for overcoming systemic barriers in this transition.

9.1 Limitation on the Research

- Broad scope across a complex industry. This study examines the entire food packaging industry, which is inherently broad due to the diversity of products, stakeholders, and uses of PFAS. This scope limits the depth of analysis that can be conducted on specific sub-sectors or alternative technologies.

- Diverse variables in the PFAS transition. The complexity of transitioning away from PFAS arises from the variety of substances, their functionalities, and the industrial players involved. Each product and PFAS alternative has unique requirements, leading to challenges in generalizing findings across the industry.

- Limited industry representation. While the study includes stakeholders from NGOs, academia, regulators, and some industry players, it may not fully capture the perspectives of smaller manufacturers or global producers, especially those in countries with less stringent regulations.

- Focus on developed market. The research is largely situated within the European and North American regulatory context, which may not reflect the conditions and challenges in other regions, such as Asia or Africa, where regulations and market dynamics differ significantly.

9.2 Implications for further research

- Sector-specific studies. Future research could focus on specific sub-sectors of the food packaging industry, such as fast-food packaging or biodegradable materials, to provide more targeted insights and strategies. Or a sector-specific study in the food packaging industry could be conducted focused on the transition to fluoropolymer-free alternatives.

- Comparative analysis across regions. Investigating the PFAS transition in regions with varying regulatory environments would highlight the influence of policy differences and uncover unique barriers or enablers in these contexts.

- Focus on larger companies. This research mainly focused on SMEs, but the transition process in larger companies may include other difficulties.

- Evaluation of emerging alternatives: A systematic assessment of new PFAS-free technologies, including their performance, cost, and scalability, could inform industry stakeholders and policymakers about viable pathways for transition.

- Stakeholder collaboration mechanisms: Further investigation into frameworks that encourage knowledge sharing and collaboration among diverse stakeholders, including NGOs, academia, and industry, could address existing gaps in cooperation.

References

Andersen, A. D. and Gulbrandsen, M. (2020). The innovation and industry dynamics of technology phase-out in sustainability transitions: Insights from diversifying petroleum technology suppliers in Norway. *Energy Research & Social Science*, 64:101447.

Bergek, A., Jacobsson, S., Carlsson, B., Lindmark, S., and Rickne, A. (2008). Analyzing the functional dynamics of technological innovation systems: A scheme of analysis. *Research Policy*, 37(3).

Brunn, H., Arnold, G., Körner, W., Rippen, G., Steinhäuser, K. G., and Valentin, I. (2023). PFAS: forever chemicals—persistent, bioaccumulative and mobile. Reviewing the status and the need for their phase out and remediation of contaminated sites.

Cousins, I., Goldenman, G., Herzke, D., Lohmann, R., Miller, M., Ng, C., Patton, S., Scheringer, M., Trier, X., Vierke, L., Wang, Z., and Dewitt, J. (2019). The concept of essential use for determining when uses of PFASs can be phased out. *Environmental Science: Processes and Impacts*, 21(11):1803–1815.

Cousins, I. T., Johansson, J. H., Salter, M. E., Sha, B., and Scheringer, M. (2022). Outside the Safe Operating Space of a New Planetary Boundary for Per- and Polyfluoroalkyl Substances (PFAS). *Environmental Science and Technology*, 56(16):11172–11179.

Crowe, S., Cresswell, K., Robertson, A., Huby, G., Avery, A., and Sheikh, A. (2011). The case study approach. *BMC Medical Research Methodology*, 11.

Curtzwiler, G. W., Silva, P., Hall, A., Ivey, A., and Vorst, K. (2021). Significance of Perfluoroalkyl Substances (PFAS) in Food Packaging. *Integrated Environmental Assessment and Management*, 17(1):7–12.

ECHA (2023). ANNEX XV RESTRICTION REPORT PROPOSAL FOR A RESTRICTION SUBSTANCE NAME(S): Per-and polyfluoroalkyl substances (PFASs). Technical report.

Gï, J., Scheringer, M., Cousins, I. T., Dewitt, J. C., Goldenman, G., Herzke, D., Lohmann, R., Ng, C. A., Trier, X., and Wang, Z. (2020). An overview of the uses of per-and polyfluoroalkyl substances (PFAS) †.

Glenn, G., Shogren, R., Jin, X., Orts, W., Hart-Cooper, W., and Olson, L. (2021). Per- and polyfluoroalkyl substances and their alternatives in paper food packaging. *Comprehensive Reviews in Food Science and Food Safety*, 20(3):2596–2625.

Hekkert, M. P., Suurs, R. A., Negro, S. O., Kuhlmann, S., and Smits, R. E. (2007). Functions of innovation systems: A new approach for analysing technological change. *Technological Forecasting and Social Change*, 74(4):413–432.

Henry, B. J., Carlin, J. P., Hammerschmidt, J. A., Buck, R. C., Buxton, L. W., Fiedler, H., Seed, J., and Hernandez, O. (2018). A critical review of the application of polymer of low concern and regulatory criteria to fluoropolymers.

Hirt, L. F. (2024). Technocratic, techno-economic, and reactive: How media and parliamentary discourses on solar PV in Switzerland have formed over five decades and are shaping the future. *Energy Research & Social Science*, 108:103378.

Karinen, A. K., Tobi, H., Devilee, J., de Blaeij, A. T., and Gabbert, S. (2024). Citizens' opinions on (non-)essential uses of persistent chemicals: A survey in seven European countries. *Environmental Science & Policy*, 153:103666.

OECD (2020). PFASs and alternatives in food packaging (paper and paperboard): Report on the commercial availability and current uses Series on Risk Management No. 58 PFASs and Alternatives in Food Packaging (Paper and Paperboard) Report on the Commercial Availability and Current Uses. Technical report.

Panieri, E., Baralic, K., Djukic-Cosic, D., Djordjevic, A. B., and Saso, L. (2022). PFAS Molecules: A Major Concern for the Human Health and the Environment. *Toxics 2022, Vol. 10, Page 44*, 10(2):44.

Prevedouros, K., Cousins, I. T., Buck, R. C., and Korzeniowski, S. H. (2006). Sources, fate and transport of perfluorocarboxylates.

Reinikainen, J., Bouhoulle, E., and Sorvari, J. (2024). Inconsistencies in the EU regulatory risk assessment of PFAS call for readjustment. *Environment International*, 186:108614.

Rudin, E., Glüge, J., and Scheringer, M. (2023). Per- and polyfluoroalkyl substances (PFASs) registered under REACH—What can we learn from the submitted data and how important will mobility be in PFASs hazard assessment? *Science of the Total Environment*, 877.

Schaider, L. A., Balan, S. A., Blum, A., Andrews, D. Q., Strynar, M. J., Dickinson, M. E., Lunderberg, D. M., Lang, J. R., and Peaslee, G. F. (2017). Fluorinated Compounds in U.S. Fast Food Packaging. *Environmental Science and Technology Letters*, 4(3):105–111.

Schiavone, C. and 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.

Simona A Bălan; Thomas A Bruton; Kimberly G Hazard (2023). *Toward a PFAS-free Future: Safer Alternatives to Forever Chemicals*, volume 81.

Spyrakis, F. and Dragani, T. A. (2023). The EU's Per- and Polyfluoroalkyl Substances (PFAS) Ban: A Case of Policy over Science.

Steindal, E. H. and Grung, M. (2021). Management of PFAS with the aid of chemical product registries—an indispensable tool for future control of hazardous substances. *Integrated Environmental Assessment and Management*, 17(4):835–851.

Strakova, J., Schneider, J., and Cingotti, N. (2021). Throwaway Packaging, Forever Chemicals European wide survey of PFAS in disposable food packaging and tableware. Technical report.

Sunderland, E. M., Hu, X. C., Dassuncao, C., Tokranov, A. K., Wagner, C. C., and Allen, J. G. (2019). A review of the pathways of human exposure to poly- and perfluoroalkyl substances (PFASs) and present understanding of health effects.

The European Commission (2019). COMMISSION RECOMMENDATION (EU) 2019/ 794 - of 15 May 2019 - on a coordinated control plan with a view to establishing the prevalence of certain substances migrating from materials and articles intended to come into contact with food - (notified under document C(2019) 3519). Technical report.

Trencher, G., Rinscheid, A., Rosenbloom, D., and Truong, N. (2022). The rise of phase-out as a critical decarbonisation approach: a systematic review. *Environmental Research Letters*, 17(12).

Trier, X., Taxvig, C., Rosenmai, A., and Pedersen, G. (2018). *PFAS in paper and board for food contact: Options for risk management of poly-and perfluorinated substances.* Nordic Council of Ministers.

Tziva, M., Negro, S. O., Kalfagianni, A., and Hekkert, M. P. (2020). Understanding the protein transition: The rise of plant-based meat substitutes. *Environmental Innovation and Societal Transitions*, 35:217–231.

Verschuren, P. and Doorewaard, H. (2010). Designing a Research Project. Technical report.

Wang, Z., Buser, A. M., Cousins, I. T., Demattio, S., Drost, W., Johansson, O., Ohno, K., Patlewicz, G., Richard, A. M., Walker, G. W., White, G. S., and Leinala, E. (2021). A New OECD Definition for Per- And Polyfluoroalkyl Substances. *Environmental Science and Technology*, 55(23):15575–15578.

Washington State Department of Ecology Olympia (2021). Per- and Polyfluoroalkyl Substances in Food Packaging Alternatives Assessment. Technical report.

Wieczorek, A. J. and Hekkert, M. P. (2012). Systemic instruments for systemic innovation problems: A framework for policy makers and innovation scholars. *Science and Public Policy*, 39(1):74–87.

Wollin, K. M., Batke, M., Damm, G., Freyberger, A., Gundert-Remy, U., Mangerich, A., Hengstler, J. G., Partosch, F., Schupp, T., Sonnenburg, A., and Foth, H. (2023). PFASs–restriction proposal commentary on ECHA's Annex XV restriction report, proposal for a restriction, March 2023.

Zabaleta, I., Blanco-Zubiaguirre, L., Baharli, E. N., Olivares, M., Prieto, A., Zuloaga, O., and Elizalde, M. P. (2020). Occurrence of per- and polyfluorinated compounds in paper and board packaging materials and migration to food simulants and foodstuffs. *Food Chemistry*, 321.

A Interview questions

Interview questions to companies that sell alternatives to PFAS (BO, MF1, MF2, MF3, MF4)

1. To what extent the recognition of the PFAS ban impacted your business?
2. What factors hinder a rapid transition towards PFAS-free alternatives? Explain per barrier below
   - Technical and performance challenges (material properties/limited availability of proven alternatives)
   - How does the performance of your PFAS alternative compare to PFAS itself?
   - Are there any technological or innovation challenges that need to be addressed to ensure a successful transition to PFAS-free alternatives?
   - What is the biggest financial hurdle for companies transitioning to your PFAS-free alternative?
   - Have any safety regulations in the food packaging industry hindered your market expansion?
3. Who do you believe plays a key role in overcoming these barriers, and how can they help unlock opportunities for improvement? Explain per barrier
4. What strategies or actions do you believe would be most effective in overcoming these barriers? Explain per barrier
5. What is your role as an innovator in the transition towards PFAS-free alternatives?
6. How do you perceive the role of government regulations in facilitating or hindering the transition to PFAS-free alternatives?
7. Is the resource mobilization a bottleneck in the transition towards PFAS-free alternatives on a big scale?

Interview questions to other stakeholder types (PR1, PR2, CI1, AE, NG, CI2):

1. What do you consider to be the primary barriers to the adoption of PFAS-free alternatives in the food packaging industry? Explain per barrier
   - Technical and performance challenges (material properties/limited availability of proven alternatives):
   - Economic and financial barriers (cost of transition in entire supply chain): What are the economic impacts of transitioning to PFAS-free alternatives for your company/industry?
   - Regulatory and compliance issues (many safety standards in food industry):

2. Who do you believe plays a key role in overcoming these barriers, and how can they help unlock opportunities for improvement? Explain per barrier
3. What strategies or actions do you believe would be most effective in overcoming these barriers? Explain per barrier
4. How do you perceive the role of government regulations in facilitating or hindering the transition to PFAS-free alternatives? (if not answered already)
5. What level of collaboration exists between companies, regulators, and NGOs in the push towards PFAS-free alternatives?
6. Are there any technological or innovation challenges that need to be addressed to successfully transition to PFAS-free alternatives?
7. Which company within the food packaging industry do you identify as the first mover in transitioning towards PFAS-free alternatives?
8. Are you familiar with fluoropolymers, and should they be exempt from the PFAS ban like in medical instruments?