The barriers and opportunities for increasing plastic recycling for food contact materials.

Assessing the quantifiable risks and societal concerns for additives in plastic recycling.

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Abstract.

Given European legislation and the shift towards a circular economy, the Netherlands will likely need to recycle more plastic for food contact materials. This thesis examines the barriers and opportunities for increasing the production of food-grade recycled plastic from household waste in the Netherlands via a thematic analysis of interviews with stakeholders in the Dutch plastic recycling system. Furthermore, the thesis focuses on the risks and concerns associated with phthalates and additives in recycled plastic used in food contact materials.

Stakeholders have identified the quality of the waste stream as the primary barrier to plastic recycling. The risk assessment reveals potential health risks associated with phthalates, particularly when higher amounts of recycled plastic are utilized in food contact materials compared to the current scenario. The concern assessment highlights that the issue of additives in recycled food grade plastic is a matter of concern for society. This concern arises due to varying stakeholder priorities and attitudes, with some stakeholders overlooking the risks associated with additives in recycled food contact materials and focusing on other potential risks like chemicals in recycled products. The potential for social conflict and mobilization and persistence of the problem further contribute to societal concern. Consequently, recycling more plastic for food contact materials poses an increased risk to human health, which demands careful and effective management. Further research into the origin of phthalates in recycled plastic is highly suggested.

To enable increased recycling while mitigating health risks, it is suggested to prioritize the improvement of the plastic waste stream's quality. Therefore, future policies should focus on enhancing waste stream quality rather than solely increasing recycling targets.

Improving the quality of the plastic waste stream in the Netherlands is a complex task encompassing various aspects. This thesis identifies three suggestions, as indicated by stakeholders, to enhance waste stream quality: incentivizing the separation company, design-for-recycling strategies, and chemical recycling. Among these suggestions, design-for-recycling is the most promising as it improves waste stream quality from early stages, leading to system-wide benefits. Further research into all three suggestions is strongly recommended.

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1. Introduction.

1.1 Plastics and their use.

One of the most common materials on today's global market is plastic. Plastic is a cheap and easily mass-produced material. It is used in many different aspects of society and many different products for a wide variety of appliances. It is commonly used in food packaging, construction material, clothing, household appliances, electronic products, laboratory environments, and in everyday utensils. Of these different appliances, food packaging is the most common, using 40% of plastics in the Netherlands (Verrips et al., 2019). Plastic has become an irreplaceable resource in today's society (Geyer et al., 2017).

Because plastics are used in a very wide range of products, a variety of plastic types is used and many different additives are added to make the plastics more suitable for certain applications (Pfaendner, 2006). Plastics consist of monomers extracted from fossil fuels. These monomers are then linked together in a chain creating a polymer (Geyer et al., 2017). Examples of additives are heavy metals to stabilize or colour the plastic, Flame-retardants to reduce fire risk, and plasticizers to make plastics more flexible (Turner, 2018).

Because plastic is not or is very slowly biodegradable, plastic ending up in the environment is a major concern. Large amounts of plastics have already entered the aquatic environment, often referred to as "the plastic soup" (Chick, 2009). Furthermore, plastics tend to break down into smaller forms of plastic over time. These smaller forms of plastic are often referred to as microplastics. Because of this, plastics can be found throughout the environment, in soil, water, animals, and humans (Cocca et al., 2020).

1.2 Plastic recycling.

Besides problems related to plastic ending up in the environment, a major concern for plastic usage is the CO2 emitted when producing plastic. To reduce CO2 emissions and avoid waste production the Netherlands is trying to change its economic structure from a linear economy to a circular economy. A large focus of policy for the circular economy is plastic recycling. An increase in plastic recycling is already taking place, Coca-Cola's PET bottles for example are made of 100% recycled PET (*100% recyclen*, n.d.). And the European Commission has proposed new legislation which would make recycled content mandatory in packaging material (European Comission, 2022). Since an increase in recycling is necessary in the Netherlands the first part of this research focuses on barriers and opportunities to increase plastic recycling.

Plastic recycling in the Netherlands is a complicated process involving many different stakeholders. Some stakeholders take care of the waste side of the plastic recycling system, they collect the plastic, separate, and recycle it. Then there are stakeholders on the production and use side of the plastic recycling system, they produce packaging, sell it, and consume it. Besides stakeholders that handle the waste or produce and consume the products, a stakeholder is enforcing the EPR (Extended Producer Responsibility) scheme in the Netherlands. This corporation is called Afvalfonds, Afvalfonds is paid by corporations that put plastic packaging on the market and uses this money to fund the unprofitable parts of the recycling process of plastic. Afvalfonds for example pays the separation company for the amount of separated plastic they deliver to the recycling company. (*Wij Zijn Stichting Afvalfonds Verpakkingen | Afvalfonds Verpakkingen*, n.d.)

A problem when recycling plastic is the contamination of the waste stream. During the consumption and end-of-life phase of plastic products, plastics can get contaminated with other substances such as chemicals or organic waste. When a waste stream is contaminated the waste stream can become unrecyclable. Or, if the plastic is still recyclable these contaminated streams can cause the recyclate to be of lower quality or contain toxic materials, others than the before described additives (Eriksen et al., 2018).

Currently, 57% of plastic packaging waste is recycled in the Netherlands, this is the third-highest recycling rate in the European Union (*EU-27: Recycling Rate of Plastic Packaging by Country*, 2022). This recycling rate could reach 72% in a utopic scenario (Brouwer et al., 2020). For the coming years the Netherlands is aiming to increase their plastic packaging recycling rate, a component of achieving this goal is to promote chemical recycling alongside the current practice of mechanical recycling (Waterstaat, 2020).

There are several ways to recycle plastic. The most common is mechanical recycling. During mechanical recycling plastics are reduced to a small size by grinding them, to then melt the separated plastic types into a new recycled plastic. During chemical recycling, different chemical processes are used to break down plastic into its building blocks, oil. This can then be used to create new plastic, resulting in a cleaner end-product against higher energy and environmental costs (Goodship, 2007).

1.3 Additives and recycling.

The additives that are added to plastic to alter its functions can pose a problem during recycling. A wide range of additives is used during plastic production, resulting in a complex mix of additives in the plastic waste stream. The problem is that when heating and remelting the plastics, these additives also tend to be mixed. The recycled plastic thus contains a mixture of different additives that were present in the recycled waste stream. Because such a wide range of additives is used it can become very hard to measure the amount of additives present in the recycled product (Janssen & Spijker, n.d.; Wagner & Schlummer, 2020).

1.4 The phthalate risk problem.

These additives are in some cases hazardous, as they can be toxic and bio-accumulative (Stenmarck et al., 2017). One of these toxic additives is phthalates, phthalates are added to plastic, as a plasticizer, to improve flexibility. Phthalates are known to be endocrine-disrupting chemicals (Zia & Mukhopadhyay, 2016). Previous studies have associated human phthalate exposure with breast cancer and diabetes in women (James-Todd et al., 2012; López-Carrillo et al., 2010). Prenatal exposure to phthalates was associated with negative effects on reproductive development in male newborns (Suzuki et al., 2012). Besides the fact that phthalates are toxic, they migrate from plastic. Phthalates can migrate into food from food packaging (Benjamin et al., 2015; Hahladakis et al., 2018; Yang et al., 2019; Zia & Mukhopadhyay, 2016) but they can also migrate into the air and have been found in house dust, surface water, soils, and cosmetics (Dewalque et al., 2014; Rustagi et al., 2011). For this reason, phthalates are currently banned from use in plastic in Europe (Benjamin et al., 2015).

Recycling, however, seems to be a source of phthalates as phthalates tend to be more present in recycled products (Coniglio et al., 2020; Leslie et al., 2016; Pivnenko et al., 2016; Z. Xu et al., 2020). The specific reason for these phthalates to be present in recycled products remains unclear, but phthalates are released from plastic during the recycling process (Hahladakis et al., 2018). Undas et al. (2023) suggests that phthalates in recycled plastic originate from other polymers and end up in the to be recycled plastic during the collection phase. They could for example be migrating from older plastics that still contain phthalates into the plastic that is eventually recycled. The specific plastic type does not seem to have a large influence on the presence of phthalates in recycled plastic. So, because phthalates tend to have a higher presence in recycled plastic than in virgin plastic, recycled plastics pose a larger risk to human health than virgin plastics. Especially recycled plastics used in food contact materials are risky since phthalates migrate into the food from the recycled plastic and thus enter the human metabolism. This is seen as the most important phthalate exposure pathway for humans (Dewalque et al., 2014). This study focuses on the phthalate risk problem and the risks related to additives during plastic recycling. From now on, human exposure to phthalates via recycled plastic in food contact products shall be referred to as "the phthalate risk problem".

1.5 Risk characterization.

To study the phthalate risk problem this chapter characterizes the risk problem based on literature and comparison with other risk problems. By doing so a framework to assess the phthalate risk problem is formed.

1.5.1 Types of risk problems.

There are multiple ways to classify risk problems. The IRGC (International Risk Governance Council) describes five different types of risk problems. There are simple risk problems, complexity-induced risk problems, uncertainty-induced risk problems, interpretative ambiguity-induced risk problems, and normative ambiguity-induced risk problems (Renn, 2006). They are described shortly below:

Simple risk problem: A risk problem with clear cause-effect relationships. (e.g., falling off a bike when the road is slippery.)

Complexity-induced risk problem: A risk problem that has unclear cause-effect relationships. Effects often occur after a long period of time, can have multiple causes, and hit individuals differently. Making the problem hard to define and analyse. (e.g., sophisticated chemical facilities, large infrastructure, critical loads to ecosystems)

Uncertainty-induced risk problem: A risk problem with large uncertainties on the scientific or technical front. Uncertainties can often be reduced through research, but even though large amounts of research have been conducted, some problems remain very uncertain. (e.g., terrorist attacks, natural disasters)

High complexity and uncertainty risk problems often result in ambiguity-induced risk problems, of which there are two types:

Interpretative ambiguity-induced risk problem: An interpretative ambiguity-induced risk problem has large variations and uncertainties in how the results of a risk assessment are interpreted by different stakeholders. (e.g., low concentration of genotoxic substances, food supplements and hormone treatment of cattle)

Normative ambiguity-induced risk problem: A normative ambiguity-induced risk problem has large variations in what can be seen as a tolerable risk. This often occurs when different stakeholders are affected differently by a risk. But it sometimes has to do with personal concepts of what can be regarded as safe (e.g., passive smoking, nuclear power, and genetically modified food).

The phthalate risk problem contains characteristics associated with an interpretative and a normative ambiguity-induced risk problem. The tolerable amount of phthalates can be interpreted differently by different stakeholders, making the problem interpretative. Furthermore, different stakeholders within the plastic recycling system can have a different opinion on what is safe, as there are many trade-offs made within the system, making the problem normative.

1.5.2 Risk classification.

A simplification of risk classification has been done by Aven & Renn (2020). Separating risk problems into three classes. The simple risk class, the uncertainty risk class and the value differences risk class. When using this classification system, the above-mentioned types of risk problems can be subdivided into these three classes as shown in table 1.

Table 1: Risk problem division into three different risk classes.

Risk classes	Risk problems
Simple risk class	Simple risk problem
Uncertainty risk class	Complexity-induced risk problem
	Uncertainty-induced risk problem
	Interpretative ambiguity-induced risk problem
Value differences risk class	Complexity-induced risk problem
	Uncertainty-induced risk problem
	Interpretative ambiguity-induced risk problem
	Normative ambiguity-induced risk problem

All three risk classes have different influencing factors. The simple risk class has almost no influencing factors, the risk thus becomes simple. The uncertainty risk class is influenced by a lack of understanding of causes of the risk, by the complexity of the risk and by the amount of interpretative ambiguity (different understandings of how the risk assessment should be interpreted). The value differences risk class has the most influencing factors. Influencing factors of the value differences risk class are priorities of stakeholders, risk attitude (how willing stakeholders are to take the risk), ubiquity (geographical spread of the damage), persistence (how long the damage lasts), reversibility of the damage, delayed effect (a long time between interaction with the risk and occurrence of damage) and the potential for social mobilisation (Aven & Renn, 2020). Using this classification system, the phthalate risk problem belongs to the value differences risk class. The influencing factors for value differences should thus be used to generate insights into the phthalate risk problem. Knowing how different stakeholders value the risk and thus what its most important influencing factors are is useful for risk management.

To manage a risk from the value differences risk problem class a discourse-based approach is required. The discourse based approach should aim to unveil competing arguments and different values and beliefs related to the risk problem (Aven & Renn, 2020; Renn, 2006). And then try to find consensus within these beliefs. When looking at different beliefs related to risk problems. Risk perception plays a large role.

1.5.3 Risk perception.

Within risk management there are two trains of thought on how important risk perception is. On one side risk managers state that risk management should be based on a scientific cost benefit assessment whereas, public risk perception should not be included in risk management since this can lead to overregulation of risks, for example a prohibition on swimming in the open sea due to possible sharks attacks (Ball & Boehmer-Christiansen, 2007). If public risk perception is not included in risk management the approach can be seen as technocratic (Leiter, 2008). On the other side risk managers are stating that a response to public perception is necessary for risk assessment simply because risks are public and societal concerns, resulting in an approach where the most common voice is used as guidance, this is called a populist approach (Leiter, 2008). The IRGC (International Risk Governance Council) supports both sides and aims for an integrative approach of risk management where a risk assessment (based on scientific data) and a concern assessment (based on public perceptions) are both used (Renn, 2006). But, to combine these two trains of thought it is important to know what risk perception is and how it is formed.

When a risk is encountered humans react through their own personal risk construct and images. These constructs and images are called perceptions, and they differ from person to person. Human behaviour, in general, is primarily driven by perceptions as opposed to hard facts. Perception is formed via common sense reasoning, personal experience, social communication, and cultural traditions. Humans tend to use relatively consistent patterns to assess risks on an individual level (Renn, 2006). Previous research has shown that risk perception is influenced by characteristics of the hazard, characteristics of the perceiver, heuristics (mental shortcuts to quickly assess a risk), and how the risk is framed to the perceiver (Siegrist & Árvai, 2020).

1.5.4 Societal concern.

The past has proven that risk perception can play a large role in societies acceptance of a development. When risk perception is high among large parts of society one can speak of societal concern. Examples of societal concern with large impacts on the use of a new technology are GMOs (Genetically Modified Organisms) and nuclear power. GMOs encountered a large backlash from society, as it was perceived as a new and potentially dangerous biotechnology used for food production. The actual risk of the introduction of GMOs in agriculture remained vague, but the risk was perceived by the public as very high. With very dangerous possible consequences and ethics playing a large role. As a result GMOs were not easily introduced in agriculture as there was little support for this from the public (Devos et al., 2008). Looking at nuclear power, a similar situation can be identified. The hazard associated with nuclear power was found to be incredibly high, especially after the Chernobyl catastrophe in 1986. From that moment on the risk associated with nuclear power, even though it is a source of power with very little greenhouse gas emissions, was perceived as extremely high by the public (Leiter, 2008). Extensive protests were held and as a result nuclear power plants were shut down. Societies risk perception once again had a very large impact on the usage of new technologies.

Ball & Boehmer-Christiansen (2007) have identified many different drivers for societal concern. There are substance-based, value-based, process-based, and stakeholder-based origins. The phthalate risk problem has drivers originating from the latter three origins. The most important ones for the phthalate risk problem have been listed below:

Value-based origins:

Different groups address the hazard in a different way, as they have different values. One group might see it as good to recycle as much as possible while allowing a small amount of contamination, where another might feel like no contamination should be allowed at all. The justifiable amount of contamination in recycled plastic might differ per group of stakeholders.

The problem is driven by the fact that different stakeholders have different underlying feelings regarding the risk. Some people might say it is important to do as much recycling as possible, others look more at negative consequences. To what extent is recycling, plastic use and plastic reuse ethically allowed for the different stakeholders?

Process-based origins:

The problem is driven by a lack of communication between risk management, and the ones at risk. There may be little communication on phthalate presence in recycled plastics. Besides little communication playing a role there might also be little trust between stakeholders, this may result from the lack of communication but also the power differences in the system.

Stakeholder-based origins:

The problem is driven by stakeholders' differences in interests. For phthalates for example one stakeholder might see a large benefit in allowing a certain amount of phthalates so they can promote their product with higher recycling rates. Other stakeholders however may look at it from a more altruistic point of view and aim to inform the public about phthalates and its dangers. All these actions can lead to higher societal concerns.

Renn (2006) has also listed four criteria that can influence societal concern. The criteria are listed and shortly explained below.

- **Inequity and injustice**: how potential risks and benefits are divided over time, distance, and social hierarchy.
- **Psychological stress and discomfort**: to what extend is the risk associated with stress and discomfort.
- **Potential for conflict and mobilization:** the amount of public pressure on the risk problem.
- **Spill-over effects:** Externalities that are expected to occur (e.g. in other markets or in the environment).

Renn (2006) suggests using these criteria for analysis of societal concern and supplement the criteria with criteria suitable for the specific risk problem. By analysing the risk problem via the different criteria an overview of the societal concern for the risk problem at hand can be created. The criteria of relevance for the phthalate risk problem are listed in the methodology, they are drawn from the criteria as explained by Renn (2006) and the influencing factors as listed by Aven & Renn (2020), shown in section 1.5.2.

1.5.5 The phthalate risk problem: scientific risk assessment and concern assessment.

As the phthalate risk problem is a normative ambiguity induced risk problem (Devilee et al., 2016) falling in the value differences class it is important to approach the problem using a risk assessment and a concern assessment as suggested by the IRGC. The risk assessment focusses on the health risks related to phthalates in recycled plastics in food contact material, the risk assessment is probably an overestimation of reality as it aims to depict a worst-case scenario. The concern assessment focusses on the risks related to additives in recycled plastic in food contact products, from now on referred to as "the additive risk problem" and how these are dealt with and perceived by stakeholders in the value chain of recycled plastic. By doing so the concern assessment depicts how high the societal concern is for the additive risk problem. This then depicts the urgence of risk management and gives insight into the relations between stakeholders regarding the additive risk problem. The two assessments are further explained in the methodology section.

1.6 Objective and research questions.

This study focuses on the Netherlands, as this is one of the frontrunners in plastic collection and plastic recycling within Europe (*EU-27: Recycling Rate of Plastic Packaging by Country*, 2022). It aims to contribute to insights into barriers and opportunities for generating more food grade recycled plastic from household waste in the Netherlands. To achieve the aim, the following three research questions shall be answered.

Research questions

1. *What key barriers and opportunities do stakeholders indicate for increasing plastic recycling for food contact materials?*
2. *What health risks are connected to phthalates present in recycled plastic in food contact items?*
3. *What is the societal concern for additives in recycled plastics as indicated by stakeholders in the value chain of recycled food contact products?*

The research questions shall be answered by combining interviews with a thematic analysis, a risk assessment, and a concern assessment. The thematic analysis is applied to create insights into the general barriers and opportunities present in the Dutch plastic recycling system. The risk assessment is used as a case study to show the health risks related to phthalates in recycled plastic in food contact products, and thus the possible health risks related to additives and plastic recycling. The concern assessment shows how concerning the additive risk problem is for the Dutch society and generates insights into the different values, perspectives, and attitudes of stakeholders in the Dutch plastic recycling system.

This thesis consists of three result chapters answering the three questions, each result chapter is concluded with a short discussion. The thesis is then concluded with an overall discussion and conclusion chapter, answering and connecting all three research questions together.

2. Methodology.

To answer all three research questions multiple different methodologies were used. To collect data, literature study, stakeholder identification and semi-structured interviews were used. To analyse the collected data a thematic analysis, deductive analysis, risk assessment, and concern assessment were conducted. Table 2 gives an overview of what methodologies were applied to answer what research question.

Table 2: Methodologies applied per research question.

Methodologies					
	Data collection			**Data analysis**	
RQ1	Literature study	Stakeholder identification	Semi-structured interviews	Thematic analysis of interviews	
RQ2	Literature study				Risk assessment
RQ3	Literature study	Stakeholder identification	Semi-structured Interviews	Deductive analysis of interviews	Concern assessment

2.1 Data collection.

During the research three different methodologies to collect data were used. First, a literature study was conducted, then a stakeholder identification was done, and lastly semi-structured interviews were conducted. The three data collection methods are further described below.

2.1.1 Literature study.

During the research a literature study was conducted. To find literature the search engines: “WUR library”, “Google scholar”, and “SCOPUS” were used. If a relevant article was found, other relevant articles were often identified by looking at the references of said article. The search aimed to find scientific sources that contain useful information by using a combination of the following or similar search terms:

RQ1: *Stakeholders recycled plastic value chain Netherlands, legislation Dutch plastic recycling system, Mechanical recycling Netherlands, Chemical recycling Netherlands, Dutch plastic recycling system, design-for-recycling, separation methods recycling Netherlands.*

RQ2: *Health hazards phthalates, migration behaviour phthalates, food consumption data Netherlands, dose-response relation phthalates, Risk assessment plastic/phthalates, phthalate presence in recycled plastic.*

RQ3: *MOSH, MOAH risks, environmental impact plastics, additives, risk governance strategies.*

The sources were accessed in the period from January until July 2023. If a relevant article was found it was added to a database of relevant articles and grouped under the topic it related to. This was an iterative process, so during the literature study more and more article groups were created, so that these could be accessed easily during the relevant steps of the research. The group topics were: *Recycling, legislation, risk assessment, separation, general info, additives, risk perception, impact, recycling.*

2.1.2 Stakeholder identification for interviews.

During the stakeholder identification relevant stakeholders in the Dutch plastic recycling system were identified. The stakeholder identification focused on finding stakeholders that got into contact with the plastic stream, a spreadsheet was build containing all identified stakeholders and their contact details. This spreadsheet was then used to reach out to the stakeholders, in total a message was sent to 39 stakeholders, via mail, phone, or via another route (e.g., contact form). Of the 39 contacted stakeholders 6 reacted positively and wanted to participate in an interview. At the end of the interviews the stakeholders were asked if they had other contacts within the system that would potentially wish to participate. This did not result in many new contacts as the companies were often not allowed to share this information. Table 3 shows how many interviews were conducted per stakeholder group.

Table 3: Overview of the interviews done per stakeholder group.

Stakeholder group	Interviewed
Packaging producer	1
Brand owner	0
Retail	0
Consumer organisation	1
Collection company	1
Separation company	1
Recyclers	2

2.1.3 Semi-structured interviews.

To collect data for RQ1 and RQ3 semi-structured interviews were conducted. The interviews took about half an hour and were held in Dutch. The most important questions were about the priorities of stakeholders, the advantages and disadvantages of recycling and how the stakeholders expected the plastic system to change in the future. The interviews were semi-structured, which allowed for further questioning when interesting topics emerged. The interviews were done in person or over teams, all interviews were recorded for transcription purposes. Transcription was done using the word text to speech function, and then proofreading and filtering out the mistakes, the transcriptions were then uploaded to atlas.ti for further analysis.

2.2 Data analysis.

2.2.1 Thematic analysis of interviews.

To uncover qualitative information from the interviews a thematic analysis as described by Guest et al. (2012) was conducted. During the analysis the 6 different interviews were read multiple times to uncover the most important thematic segments (quotes). These segments were coded using atlas.ti, the codes indicated what the segment was about. These codes had two layers to them, the first stated what the segment was about in general, for example “risk”. The second layer made the code more specific, for example “Health risk”. When all 6 interviews were coded links between the different codes were assessed and interpreted, resulting in overarching themes. The most important and characteristic quotes were then either directly translated or described to depict the different themes. All of this was done in an iterative manner and new themes sometimes emerged from initial themes. The resulting themes were then used to answer research question one.

2.2.2 Risk assessment.

In the risk assessment scientific information regarding phthalates and their toxic effects on humans was analysed. This was done by first assessing what health hazards are affiliated with phthalate exposure and then calculating the expected amount of exposure. The EFSA Panel on Food Contact Materials, Enzymes and Processing Aids (CEP) et al. (2019) has done extensive research on the 5 most common phthalates, the EFSA research contains a thorough analysis of articles on the toxicological effects of phthalates. From this analysis the EFSA has derived the most critical toxicological effects. Based on these critical effects and by multiplying them with an uncertainty factor the EFSA has derived a TDI (tolerable daily intake).

To assess whether there were potential health effects for phthalates in recycled plastic in food contact materials the TDI as determined by the EFSA, was compared to the expected daily intake of phthalates from recycled plastic in food contact materials. The potential exposure was calculated for a diet in which all food and beverage was consumed from plastic packaging made of 100% recycled plastic. Since there is very little data on different migration factors for different types of foods and beverages, migration data on oil represented migration data into foods with high fat contents, and migration data on mineral water represented migration data for all beverages (Q. Xu et al., 2010). The risk assessment was done to assess the risk for the highest probable exposure of Dutch consumers to phthalates. This is why the upper 95% consumption data was used. The risk assessment was done for adults and not for children since adults have about a factor 6 higher consumption and about a factor 4 higher weight. So, phthalate intake per kg bodyweight is higher for adults then for children. The expected daily phthalate intake was calculated using the following equations.

First the amount of phthalates present in a package was calculated using equations 1 and 2:

Equation 1. $Phthalates\ in\ packaging\ material\ food\ (\mu g/package) = Phthalates\ in\ recycled\ plastic\ (\mu g/g) * packaging\ weight\ food\ (g/package)$

Equation 2. $Phthalates\ in\ packaging\ material\ drink\ (\mu g/package) = Phthalates\ in\ recycled\ plastic\ (\mu g/g) * packaging\ weight\ drink\ (g/package)$

In which:

- *Phthalates in recycled plastic (µg/g) - taken from Pivnenko et al. (2016)*
- *Packaging weight beverage (g/package) - taken from* Recycling network Benelux (2019)
- *Packaging weight food (g/package) - taken from Maga et al. (2019)*
- *Phthalates in packaging material food/beverage (µg/package) - calculated*

Then, the concentration of phthalates in food or beverages was calculated using equations 3 and 4:

Equation 3. $Phthalate\ concentration\ food\ (\mu g/g) = \frac{Phthalate\ \ in\ packaging\ material\ food\ (\mu g/package) * Migration\ factor\ food}{Amount\ of\ food\ in\ package\ (g/package)}$

Equation 4. $Phthalate\ concentration\ drink\ (\mu g/g) = \frac{Phthalate\ \ in\ packaging\ material\ drink\ (\mu g/package) * Migration\ factor\ drink}{Amount\ of\ drink\ in\ package\ (g/package)}$

In which:

- *Phthalates in packaging material food/beverage (µg/package) - taken from equations 1 and 2.*
- *Migration factor food (no unit) - taken from the migration factor for oil as determined by Q. Xu et al. (2010)*
- *Migration factor beverage (no unit) - taken from the migration factor for mineral water as determined by Q. Xu et al. (2010).*
- *Amount of beverage and food in packaging (g/package) - assumed to be 500g.*
- *Phthalate concentration food/beverage (µg/g) – calculated.*

The total daily intake of phthalates was then calculated using equation 5:

Equation 5. $$Daily\ intake\ phthalates\ (\mu g/(kg_{bw} * day)) = \frac{Phthalate\ concentration\ food\ (\mu g/g) * Food\ consumption\ (g/day) + Phthalate\ concentration\ drink\ (\mu g/g) * Drink\ consumption\ (g/day}{Bodyweigh\ \ (kg_{bw})}$$

In which:

- *Phthalate concentration food/beverage (µg/g) - taken from equations 4 and 5.*
- *Food consumption (g/day) - calculated by combining the consumption data on high fat foods (dairy, meat, fish, and oil) as determined for the higher 95% of the Dutch population by the RIVM* (RIVM, 2021).
- *Beverage consumption (g/day) - calculated by combining the consumption data on beverages (non-alcoholic and alcoholic) as determined for the higher 95% of the Dutch population by the RIVM* (RIVM, 2021).
- *Bodyweight (kg_{bw}) - assumed to be 70kg.*
- *Daily intake phthalates (µg/(kg_{bw}*day)) – calculated.*

The daily intake of phthalates is then converted to mg/(kg_{bw}*day) so the daily intake can be compared to the tolerable daily intake. To compare the daily intake to the TDI the Risk Quotient (RQ), was then calculated using equation 6.

Equation 6. $$\frac{Daily\ intake\ phthalate\ \ (\mu g/(kg_{bw} * day))}{Tolerable\ Daily\ Intake\ (\mu g/(kg_{bw} * day))} = Risk\ Quotient$$

As the intake of three different types of phthalates was calculated they were grouped. This was done using the Relative Potency factors as described by the EFSA to convert all phthalates to the same phthalate type, in this case DEHP-equivalents.

2.2.3 Concern assessment.

To supplement the scientific risk assessment a concern assessment was conducted. The concern assessment aimed to show how concerning the additive risk problem is to society and unveil relevant social information for risk managers and policy makers trying to deal with the risk problem. Based on the risk characterization as done in the introduction, criteria have been established to test for societal concern. The criteria shown below have been selected because the risk problem falls in the value-differences risk class, risk managers should thus aim to create consensus among stakeholders on the best way to deal with the risk problem. All criteria thus relate to unveiling differences in how the risk affects and is seen by different stakeholders in the system. Insight into the different criteria was gained through interviews with stakeholders, deductive analysis of these interviews, literature study, and using data from the risk assessment. A division of how insights into the different criteria were created is given in table 4. The criteria are described shortly below.

Table 4: Criteria and how their presence was analysed.

Criteria	Interviews	Literature study	Risk assessment
Difference in priorities of stakeholders	X		
Difference in risk attitudes	X		
Psychological stress and discomfort			
Potential for conflict and mobilization	X		
Inequity and injustice			
Spill-over effects		X	
Persistence			X

Difference in priorities of stakeholders

Differing priorities of stakeholders can make it harder to find consensus among stakeholders. It is important to show which stakeholder or stakeholder group prioritizes which benefits and risks associated with the risky activity (or promotion/marketing of it).

Difference in risk attitudes

Different stakeholders can have a different attitude towards the risk. What is an acceptable risk to one stakeholder may be unacceptable to another. It is important to unveil this difference in risk attitude as it can make it harder to find common ground on how to deal with the risk in policy making.

Psychological stress and discomfort

It is important to know if a risk causes psychological stress and discomfort among stakeholders. When a high psychological stress and discomfort is associated with a risk, risk management becomes more urgent, and finding consensus among stakeholders can become harder. During this research however, interviews were directed at the organisation level and not at the individual level. As a result, the psychological stress and discomfort criterion could not be assessed based on the interviews. This criterion was thus not considered in this concern assessment.

Potential for conflict and mobilization

Societal concern becomes higher when a risk has the potential to give rise to conflict and public mobilization. When there is a lot of potential for this, risk management becomes more urgent but should also be more delicate.

Inequity and injustice

As a risk can have different effects on different layers of society, different geographical locations, and different points in time (delayed effect), this can influence the way different stakeholders react to the problem. To be able to create consensus on the risk problem it thus becomes important to know how different stakeholders are affected by the risk. During literature study however, no data on plastic consumption across different social layers within the Netherlands could be found. The inequity and injustice criterion was thus not considered in this concern assessment.

Spill-over effects

A risk problem can have different externalities outside of its own system. It may for example cause harm to the environment, the economic market, or the cultural sector. These spill-over effects can influence stakeholders active in those markets in a different way, and make a risk problem of higher societal concern, as it influences a large aspect of society.

Persistence

The persistence of the hazard associated with the risk can influence the urgence of risk management. If a hazard is very persistent and hard to reverse, risk management becomes more urgent.

The results of the concern assessment were then summarised in the following table. Giving an overview of the most important factors that influence the societal concern for the risk problem.

Table 5: Template of concern assessment table.

Criteria	Low presence	Medium presence	High presence
Difference in priorities of stakeholders			
Difference in risk attitudes			
Potential for conflict and mobilization			
Spill-over effects			
Persistence			

2.2.4 Deductive analysis of interviews.

To assess whether different criteria of societal concern were present during the interviews with different stakeholders a deductive analysis of the interviews was done as described by Reichertz (2014). Just like in the thematic analysis of the interviews codes were applied to different segments. But as opposed to the thematic analysis the codes were now developed beforehand, and not adjusted iteratively. The codes used were priority, attitude, and social conflict. The codes were then applied to the segments of the interviews that showed signs of the three different criteria mentioned in the concern assessment that could be found during the interviews. The most relevant quotes were then either directly translated or their meaning was described to give an overview of the information found in the interviews.

3. Barriers and opportunities to increase plastic recycling for food contact products.

3.1 Stakeholders involved in the plastic recycling system.

The stakeholders have a large variety of knowledge about the different aspects that plastic recycling involves. The different stakeholder groups present in the Dutch plastic recycling system for food contact products that were contacted for interviews are shortly described below.

Packaging producers

For plastic packaging in food contact products many different packaging producers exist. Some packaging for the Dutch market is imported from abroad while other packaging producers are based in the Netherlands. For this research a packaging producer is interviewed that uses very little recycled plastics themselves but does have knowledge of food packaging and recycled plastic as a resource for food packaging.

Brand owners

Brand owners are corporations that design and buy packaging from the packaging producers, to package their products in. Examples of brand owners on the Dutch market are: Friesland Campina, Unilever, Nestlé, Coca-Cola (Ministerie van IenW, 2019). None of the brand owners contacted were willing to participate in an interview for this research.

Retail

Retail companies are responsible for the sale of products owned by brand owners to consumers. In the Netherlands this is often done via large supermarket chains such as Albert Heijn, Jumbo, Hoogvliet, PLUS, and COOP. The retail companies contacted however did not wish to participate in the interviews.

Consumers organisation

Consumers are a stakeholder in the plastic recycling value chain as they buy and use the plastic products that are sold. For this research a consumer organisation that represents consumer interests is interviewed instead of consumers themselves. There are many NGOs involved with plastic recycling policies. These NGOs are often lobbying for higher recycling rates and a reduction in plastic litter.

Collection company

In the Netherlands plastic waste collection is done by a variety of companies. Some companies are municipality owned and collect household plastic waste. While others are privately owned and focused on company plastic waste. For this research a municipality owned collection company is interviewed.

Separation company

In the Netherlands plastic waste is collected in two different ways. It is either source-separated, meaning that consumers throw their waste in separate bins (Plastic/Metal/Drinkingpackaging, paper, glass, compost, and general), or it is post-separated, in which case most waste is combined in the same bin and separated at the waste-separation facility. The specific task performed by sorting and separation companies thus differs per location. But in essence their task is to separate the collected plastic waste into different plastic waste streams. For this research a separation company that separates both source-separated and post-separated waste streams is interviewed.

Recyclers

After collection and separation, the plastic waste is brought to plastic recycling companies. Recyclers process the plastic waste stream into homogeneous regrinds. Which can later be used to make new plastic products. For this research two recyclers are interviewed. Both focus on creating food-grade recycled PET.

Based on the interviews with the different stakeholders three main themes emerged. The themes are: The barriers for different stakeholders, Responsibility, and Opportunities for more recycling. The themes are described below.

3.2 Theme 1: The barriers for different stakeholders.

In general, the plastic recycling system is aiming to recycle large quantities of plastic. When trying to achieve this, every stakeholder encounters different barriers. The barriers discussed in the interviews are described below.

When speaking about contamination stakeholders tend to mention different things. For the collection and separation companies the most encountered and important contamination is organic material and mixing of different plastic types. This is to be expected since they collect and sort large bulks of waste (C*ollection company, separation company*).

The recyclers, however, mention a large problem with chemical contamination of their waste. Their main concern when recycling is the occurrence of for example PET shampoo bottles. This is mainly due to the 95/5 rule[1]. As soon as there is too much non-food packaging present in the batch it becomes unrecyclable. (*Interview recycler 1, interview recycler 2*) Recycler 1 states that this law is too strict and could be made a bit more lenient, as to create more opportunities to recycle. They state: “In the end it is definitely food-grade, the plastic goes by two extruders[2] so it will become pretty clean”.

During the interviews the consumer organisation already states the first problems in producing clean waste, which is separation by the consumer. The consumer organisation states: “If you’re lucky, the consumer maybe sees the difference between plastic and paper. You don’t want to know how simplified it needs to be.” As the consumer struggles in separating the waste correctly, the waste stream starts off quite polluted. The packaging company confirms this problem and states that compostable plastics don’t work since consumers don’t understand what to do with them (*Packaging* company). The consumer organization thus prioritizes supporting the consumer in separating waste adequately. They state that they are actively trying to make the consumer separate their waste better. So that the consumer throws the plastic in the PMD bin eventually (*Consumer organization*).

The collection company also recognizes the consumer side separation problem, they state: *“The consumer wants convenience, which is a challenge.”* Which besides bad separation at home, results in unrecyclable products on the market: *“A multilayer plastic product is an advantage for the*

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[1] A law stating that the food/non-food material ratio at the extruder step of the process must be 95% food to 5% non-food if you want to produce food grade rPET. (*Recycler 1, Recycler 2*)

[2] A step of the recycling process that uses high heat to melt the plastic and later form it. Besides reshaping this step also reduces the amount of contaminants in the plastic, but exactly how much is still being discussed (Koller et al., 2022).

consumer but a disadvantage for recycling." The collection company however, as they are owned by the municipality, is required to collect all consumer waste that is offered to them, even when this is contaminated. But when contamination is high, the collection company encounters problems, as their waste is rejected by the separation companies. Furthermore, the collection companies sales department sets certain quality requirements for their waste. So, in reaction to this contamination the collection company prioritizes supporting cleaner consumer side separation via the municipality or citizens. The collection company takes the Belgian waste stream as an example. They state that the Belgian waste material is of a much higher quality than the Dutch, because of a different collection method. They have better communication and more source-separation resulting in large advantages throughout the rest of the plastic recycling system. (*Collection company*)

The separation company highlights a different barrier. The separation company produces their output stream in accordance with the so called DKR norm[3]. The separation company states that there is some discussion around the norm between the separation company and the recycler. For PE for example the norm states that 94% should be PE. But, since the norm states "as the product is" this PE products can still contain its content, its label, or a special cap, which is not PE. This then results in a discussion where the recycler states that the waste batch is below norm, while the separation company states that it is above norm. So, the separation company asks the question: "How clean is clean? How pure is pure?" Besides having discussions about the norm, the separation company finds barriers when dealing with Afvalfonds. Since the compensation for their waste streams is paid by Afvalfonds the separation company must follow Afvalfonds' objectives. Which is producing as much output as possible following the DKR norm. The separation company further explains that if they produce a cleaner output, they will have a lower quantity. And thus, get less financial compensation from Afvalfonds. So, if they find a flipflop for example, they could take it out, which would be better for the recycler, but if they are already producing according to the DKR norm, they might as well leave the flipflop in, resulting in more financial compensation. The fact is that Afvalfonds has a recycling target that needs to be met, and since the measurement point for this recycling target is at input recycler, they want the highest quantity coming from the separation company (*Collection company*). Furthermore, when the separation company asked the recycling company wether they could create a financial incentive to create cleaner waste the answer was as follows: "If you are doing it, but the other separation companies aren't then we still need the installations to separate it further." So, the separation is capable of producing a cleaner output. But feels held back by afvalfonds and the recyclers. They state: "We can go much cleaner than we are doing now." Even so, the separation company is convinced that they should focus on quality, but doesn't see the financial incentive, which gives them struggles in running their business. (Separati*on company*)

The recyclers state that just like the separation companies they have many different legislations to abide by. The hardest one to abide by is the 95/5 rule. This is why they have certain demands for the input stream coming from the separator (*Recycler 1*). Thus the fact that the DKR norm is not alligned with the 95/5 rule makes it rough for the recycler to find recyclable input for food grade recycled plastic. When looking forward, recycler 2 states that it is doubtful whether there is going to be enough clean waste available to produce the future demand of food grade rPET. The collection company confirms this struggle, and even states that some of the input for the recyclers is currently found in Belgium, as their waste stream tends to be cleaner then the Dutch waste streams. The

[3] German norm that states the allowed amount of other components in a waste-stream. Specific norms can be found here: https://www.gruener-punkt.de/de/downloads

collection company speculates and suggests that some sort of lobby should be put in place which helps translate the required quality for recyclers into municipal policy (*Collection company*).

The recyclers main problem is thus abiding by the strict 95/5 rule, recycler 1 does not necessarily see why this rule is so strict. They state: “We think that you won’t find any alarming substances in the recyclate, but rules are rules. So, we must check, abide, and correct for the 5%.” Besides dealing with the 95/5 rule, recyclers are struggling to provide recycled plastic that confirms to the demand set by packaging companies. The functionality of the recycled plastic depends on additives present in the plastic waste. Recycler 2 states: “Some additives limit the recyclability or application of the plastic.” The prior usage of the plastic waste can be a limiting factor for example, plastics that were used for vegetables in the first place are not allowed to be used for meat after recycling. This is all stated in the declaration of compliance[4] that must be delivered for every recycled plastic product. In the end everything depends on the quality of the end product for the recyclers. (Recycler 2)

The packaging producer sees this problem as well and is almost unable to find food grade rPET, thus the packaging producer uses other materials for their products (e.g. cardboard). They state that all PET trays are downcycled as a result of ending up in mixed plastic waste. So, the PET is recycled, but not into food grade rPET. The rPET currently used by the packager is from a closed loop system in which it can be proofed that material did not leave the loop, so not this rPET is not recycled from the domestic waste system. Mainly because the domestic waste system tends to have to many insecurities about contamination, caused by mixed collection. The producer company states: “The waste phase is just too hard.” (*Packaging producer*)

3.3 Theme 2: Responsibility.

During the interviews different opinions on who is responsible for barriers in the plastic recycling system, and who could bring change in the plastic recycling system were found. Often stakeholders were finding other stakeholders responsible for flaws in the system. The consumer organisation states that badly recyclable plastics and low use of recycled plastic are a problem caused by marketing. (*Consumer organization*) This idea is supported by the collection company, stating that the use of rPET was rising when virgin plastic become more expensive. But when the price of virgin plastic dropped again all companies switched back. Which according to the collection company was an indication of a low intrinsical motivation. (*Collection company*) The packaging producer confirms this by stating that retail wants virgin plastic packaging as it is more economically viable: “Supermarkets are mainly looking at finances, the tomato buyer for example is only taking finances into account and neglects sustainability” Furthermore, the packaging producer states that supermarkets really want packaged products (*packaging producer*). On the other hand, the separation company indicates a large amount of power and a willingness to change on the retail side. They state that Lidl, for example, owns shares in a large PET tray producer and in one of the largest recyclers in Germany. And that PET tray producer owns a large recycler in the Netherlands, that uses batches produced by the separation company to make granulate. This granulate is then used to make new PET trays which are then used by Lidl. In this way Lidl is actively controlling the market of recycled food-grade material. The separation company highlights that the retailers have much more power in the system then you would originally think. (*separation company*)

Besides retail, the consumer is often depicted as responsible for problems. As described before, the consumer organization states problems when it comes to accurately separating waste on the consumer side, indicating that consumers are responsible for decontamination of the waste stream.

[4] An extensive form that shows the origin of the material and all the processes it has gone through. The form is part of Regulation (EU) 2022/1616.

And the collection company recognizes this desire for convenience on the consumer side. Besides problems with separation, problems with consumer demand were mentioned by a recycling company. Especially regarding the colour of packaging, stating: “It would be nice if the consumer just accepted that recycled trays have different colours.” (*recycler 1*) The packaging company argues that consumers do have the power to bring change in the system. For example, when the packaging company started lasering their logos directly onto the skin of the fruits to further reduce packaging, the consumer reacted very positively. It was shared on social media and the packaging company was in high demand within no time. So, to quote the packaging company: “That’s it, if the consumer asks for it, something happens!” (*Packaging organisation*).

Lastly, the packaging company refers to legislation as a big source of change within the system. They state that the single use plastics directive for example has brought many new alternatives for straws on the market. These alternatives may not always be the best, “but if legislation changes, something happens.” (*Packaging producer*).

3.4 Theme 3: Opportunities for more recycling.

While conducting the interviews different thoughts on ways to increase plastic recycling became apparent. Most stakeholders seem to agree that packaging should become more universal (e.g., less types of plastic, more standardized packaging sizes for better recognition by separation machine) in the future, as this would allow for easier sorting and recycling. The consumer organisation and collection company mention this in the following ways: “Where you have to go, is less types of plastics and more mono materials in the industry.” (*Consumer organisation*), “The best for the entire recycling process would be if packaging would be as universal as possible” (*Collection company*).

The separation company agrees to this and convincingly states that the wide variety of plastic types should be limited. For now PP, PE and PET make up the main bulk. The separation company states that a new plastic can be added on the market, but if you do that they will end up in the incinerator since the separation machines will not recognize them. So, before the new plastic type can even reach the recycler the 5 large separation factories in the Netherlands will have to invest millions of Euros. This should be taken into consideration. (S*eparation company*) The packaging company agrees to this. It states that for some packaging plastic will always be the best option, but that when plastic is used the focus should be on using mono materials. (*Packaging company*). One of the recyclers also states that multilayer packaging is hard to recycle mechanically and would be more suitable for chemical recycling as this allows for breaking down plastics to the core (*Recycler 2*).

There is however some discussion around chemical recycling. Mechanical recycling is already a very expensive activity, as large quantities of energy and water are needed. Recycler 1 states: “Recycling is very energy intensive and uses large quantities of water”. When looking forward the recycler states that this water usage is especially worrying due to drinking water shortages that might occur on a more regular basis. (*Recycler* 1) The other recycler states that everything that can be mechanically recycled should be mechanically recycled, as chemical recycling is much more expensive and energy consuming than mechanical recycling. (*Recycler 2*) The collection company states that there is a high potential for chemical recycling in the coming 5 years, but that chemical recycling does also require a high enough quality input, so the expectations were higher than reality. But both mechanical and chemical recycling bring a reduction in CO_2 emissions. (*Collection company*) The packaging company also states that chemical recycling has a very high potential for food-grade recycled plastic. Mainly because this allows you to go back to the primary resources, which eventually results in 100% rPET. But the packaging company states that this technology is quite far away, about 10 to 15 years (*Packaging company*).

Another perspective on the future is the improvement of separation. The collection company states that Belgium already collects a much cleaner waste stream from the consumers, resulting in a cleaner waste stream throughout the system. According to the collection company this cleanliness is mainly due to more source-separation and a better communication. (*collection company*) The consumer company, besides actively trying to help consumers separate better. Also sees future improvements in the separation machines which would result in even cleaner waste streams: "The separation installations are definitely getting better and quicker" (*Consumer* organisation) The separating company recognizes this improvement. They state that they are currently trying to improve the separation of the low-quality mix fraction. But when doing so the commercial side of the business starts asking questions. Because when they separate this mix fraction better, you are left with a stream that is entirely unrecyclable and thus worthless. As they say themselves: "In separating you always have to look ahead at what you are left with". They can separate much cleaner, but it is often not worth it due to financial reasons and the eventual quantity of recyclable plastic will be lower (*Separation company*).

3.5 Discussion of the thematic analysis

Since an increase in recycling is required to achieve a more sustainable and circular future it is important to have a thorough understanding of the barriers within the recycling system. Currently, as shortly stated in the introduction an argument is made to have a mandatory amount of recycled content in new packaging materials (European Comission, 2022). This would mean that much more food-grade recycled plastic is required on the market. To be able to meet a higher demand of food-grade recycled plastic, recyclers need a higher quality plastic waste stream which abides by the 95/5 rule. The separation company however is producing a waste stream according to the DKR norm, which does not match the 95/5 rule. This renders the waste stream unusable for the food-grade plastic recyclers. The separation company does state a willingness to improve their systems and produce a higher quality (cleaner) waste stream. But if the separation company makes these investments, it sees no financial compensation and eventual recyclable plastic output is lower. The Afvalfonds pays for the quantity of DKR norm abiding plastic leaving the separation company, and not for the quality of the recycled plastic. As a result, a trade-off between quality and quantity is made. The separation company delivers a slightly lower quality, but a higher quantity, resulting in a higher financial return, but in lower food-grade recyclable (95/5) plastic. The separation company by itself will thus not create a higher quality plastic stream without any changes happening beforehand.

Another way to generate a cleaner plastic waste stream would be to look at improved separation at the consumer. The collection company states that the plastic waste stream in Belgium is of much higher quality due to better communication and a different collection system. On the contrary previous research on different collection strategies, showed very little improvement for the amount of plastic separated after the separation company. Indicating that little quality improvement is to be gained from adjusting the separation methods (Thoden van Velzen et al., 2019). Currently, the collection company and consumer organization are both working on communicating to consumers how to separate, but still the waste collected is quite polluted. Improved separation at the consumer thus seems hard to achieve for the Dutch plastic recycling system as different collection strategies and better communication both have minimal impacts.

From the themes another way to improve the quality of the plastic waste stream emerged. Many stakeholders suggested to create more universal packaging. Universal packaging would mean fewer plastic types involved in the entire packaging industry, only mono-material packaging, and easier recognizable packaging. This has the potential to make separation easier at both the consumer and at the separation company. If there are only a few packaging types, separation for the consumer would become easier as there are less components to consider. And as stated by the consumer organization, “If you’re lucky the consumer maybe sees the difference between paper and plastic”. For the separation company more universal packaging means that the separation machines can become more efficient, and less pollution would end up in the end stream. Further simplification of packaging materials might thus improve separation. Universal packaging can also be seen as design-for-recycling, an often mentioned concept in literature about plastic recycling (Ding & Zhu, 2023; Milios et al., 2018; Picuno et al., 2021). The idea of design-for-recycling is that the recycling phase of a product, in this case packaging, is fully considered during its design phase. Resulting in a product that is easily recognized by the consumer and separation machines, and easily recyclable by the recyclers (Ding & Zhu, 2023). The idea is strongly supported by Picuno et al. (2021), especially as this creates more recyclable plastic from the start instead of pushing impossibly achievable recycling targets even higher. This however needs to be facilitated through communication with retail and brand-owners (Gradus, 2020), who did not participate in the interviews, but do seem to have a large amount of power in the Dutch plastic recycling system. The Lidl example given by the separation company could be an example of this design for recycling.

Lastly, chemical recycling is often mentioned in the interviews as a very promising future alternative to supplement mechanical recycling. Chemical recycling could produce a much cleaner recycled product and thus create more food grade recycled plastic (Waterstaat, 2020), it is however a much more expensive process. But, as chemical recycling creates a pyrolysis oil, which can be used as a source of energy, this may not be seen as the correct solution by Afvalfonds. Because, if this oil is not used for recycling it does not help Afvalfonds achieve their recycling targets (Picuno et al., 2021). Furthermore, the potential for chemical recycling is lower than initially expected since chemical recycling still requires a certain cleanliness of the waste stream. This is both stated in the interviews and supported by Picuno et al. (2021).

The demand of a higher quality waste stream stems from the different legislations that the recycler must abide by to be allowed to market its recycled products. But also, from the demands of the packaging industry of which according to Picuno et al. (2021) 40% finds the quality of recycled plastic insufficient. When looking into the quality of recycled plastics multiple factors can be considered. The plastic product needs to be strong enough to function the way its use demands. But besides this many legislations are made to protect the consumer when consuming food products sold in recycled packaging, as highlighted by the recycler. Since potential health risks from plastic recycling from food grade products are often mentioned during interviews this research takes a case study to assess these potential health risks. The next chapter of this thesis focuses on the risks related to additives, in this case phthalates, present in recycled plastic especially since there appears to be little attention for this specific risk.

4. Risk assessment: phthalates in recycled plastic.

4.1 Hazards.

EFSA Panel on Food Contact Materials, Enzymes and Processing Aids (CEP) et al. (2019) has done an extensive review of toxicological research on five different types of phthalates. These five types are DBP (di-butylphthalate), BBP (butyl-benzyl-phthalate), DEHP (di-2-ethylhexyl phthalate), DINP (di-isononylphthalate), and DIDP (di-isodecylphthalate). The different phthalates were mostly tested on rats and a variety of potential health impacts were found for them. Health impacts found for phthalate exposure were: Immune effects (You et al., 2014), neurological or neurodevelopmental effects (Braun, 2017), developmental effects (Waterman et al., 1999), metabolic effects (Kim & Park, 2014), liver effects (Lington et al., 1997), and negative effects on reproduction (Clewell et al., 2013; Lee et al., 2004; Tyl et al., 2004; Wolfe & Layton, 2003). From these different effects the most sensitive effect of exposure to DBP, BBP and DEHP were found to be negative reproductive effects. For DINP and DIDP it was found that the most sensitive effect was on liver functioning, DINP did also influence reproductive effects negatively as well, but for higher concentrations then the liver effects. The EFSA Panel then determined the tolerable daily intake (TDI) of the different phthalates for humans based on the NOAELs (No Observed Adverse Effect Level) and LOAELs (Lowest Observed Adverse Effect Level) of the most sensitive effect. More specifically, DBP has a LOAEL of 2 mg/(kg_{bw}*day) as determined by Lee et al. (2004) for reduced spermatocyte development and effects on the mammary gland in rats, BBP has a NOAEL of 50 mg/(kg_{bw}*day) for reduced anogenital distance as determined by Tyl et al. (2004), DEHP has a NOAEL of 4.8 mg/(kg_{bw}*day) for testicular effects (Wolfe & Layton, 2003), DINP has a NOAEL of 15 mg/(kg_{bw}*day) for an increased incidence of spongiosis hepatis (Lington et al., 1997), and DIDP has a NOAEL of 15 mg/(kg_{bw}*day) for effects on the liver (Exxon Biomedical sciences, 1997). Since all the effects were found in offspring during tests with pregnant rats (except for the DIDP, which was found in dogs) an uncertainty factor of 100 for NOAELs and 200 for LOAELs was applied by the EFSA to calculate the TDI for humans. An overview of the most sensitive effect, NOAELs, uncertainty factors and TDIs as determined by the EFSA is shown in table 6.

Table 6: The different effects and Tolerable Daily Intakes for the five phthalate types (EFSA Panel on Food Contact Materials, Enzymes and Processing Aids (CEP) et al., 2019).

Phthalate	Most sensitive effect	NOAEL (mg/(kg_{bw}*day))	uncertainty factor	TDI (mg/(kg_{bw}*day))
DBP	Reproductive effects	2 (LOAEL)	200	0.01
BBP	Reproductive effects	50	100	0.5
DEHP	Reproductive effects	4.8	100	0.05
DINP	Liver	15	100	0.15
DIDP	Liver	15	100	0.15

As DBP, BBP, DEHP and DINP all have negative reproductive effects a group TDI was derived by the EFSA. The group TDI could be established since DBP, BBP, DEHP, and DINP all have similar structure, use/exposure pattern, toxicokinetics and have similar reproductive toxicity due to anti-androgenic effects. The EFSA determined the group TDI on 0.05 mg/(kg_{bw}*day) and was expressed in DEHP equivalents. For converting the different substances to DEHP equivalents RPFs (Relative Potency Factors) were calculated by dividing the TDI for DEHP by the TDI for the other phthalate (EFSA Panel on Food Contact Materials, Enzymes and Processing Aids (CEP) et al., 2019). The RPFs for the phthalates are shown in table 7.

Table 7: The RPF to express the phthalates in DEHP equivalents (EFSA Panel on Food Contact Materials, Enzymes and Processing Aids (CEP) et al., 2019).

Phthalate	RPF
DBP	5
BBP	0.1
DEHP	1
DINP	0.3

DINP was included in grouping the phthalates as there were indications that DINP also has effects on reproduction. But, this is a conservative opinion and might lead to an overestimation. (EFSA Panel on Food Contact Materials, Enzymes and Processing Aids (CEP) et al., 2019)

4.2 Exposure.

To assess the human exposure to phthalates coming from recycled plastic in food contact materials, first the amount of phthalates that enter the food need to be calculated. This is done using the initial concentration of phthalates in recycled plastic from household waste, as determined by Pivnenko et al. (2016). Pivnenko et al. (2016) only determined the initial concentration of phthalates for DBP, BBP and DEHP. As a result the estimated exposure to DINP and DIDP cannot be calculated. This initial concentration is then multiplied by the packaging size for food (Maga et al., 2019) and beverages (Recycling Network Benelux, 2019) to calculate the amount of phthalates in the packaging. The equations used to calculate the amount of phthalates in the two packaging types are described in the methodology. Table 8 and 9 show the results for filling in equation 1 and 2 for all three phthalate types.

Table 8: Results calculation of phthalates in food packaging.

Phthalate	Phthalates in recycled plastic (µg/g)	Packaging weight food (g/package)	Phthalates in packaging food (µg/package)
DBP	11	18.4	202.4
BBP	15	18.4	276
DEHP	600	18.4	11040

Table 9: Results calculation of phthalates in beverage packaging.

Phthalate	Phthalates in recycled plastic (µg/g)	Packaging weight beverage (g/package)	Phthalates in packaging beverage (µg/package)
DBP	11	16.4	180.4
BBP	15	16.4	246
DEHP	600	16.4	9840

Comparing table 8 to table 9 shows that food packaging contains more phthalates then beverage packaging due to the larger size. Furthermore, DEHP is much more present then DBP and BBP due to its higher initial value.

To calculate the amount of phthalates potentially ending up in food and beverages the calculated amount of phthalates in packaging is multiplied by the migration factor, this is then divided by the amount of food or beverage that would be in the packaging (500g) to get the amount of phthalates in 1 gram of food or beverage. The migration factor for phthalates from plastic packaging into oil and mineral water has been determined by Q. Xu et al. (2010). This migration factor was determined for keeping the oil and mineral water stored in packaging for two months at 20°C. Since no other migration factors were found it was assumed that the migration factor for oil is representative for all fatty foods, and that the migration factor for mineral water is representative for all beverages. The equations to calculate the amount of phthalates in the food and beverages are shown in the methodology. Table 10 and 11 show the results for filling in equation 3 and 4.

Table 10: Results calculation of phthalates in food.

Phthalate	Phthalates in packaging food (µg/package)	Migration factor food	Amount of food in packaging (g/package)	Phthalate concentration food (µg/g)
DBP	202.4	0.1	500	0.0405
BBP	276	0.06	500	0.0331
DEHP	11040	0.15	500	3.3120

Table 11: Results calculation of phthalates in beverages.

Phthalate	Phthalates in packaging beverage (µg/package)	Migration factor beverage	Amount of beverage in packaging (g/package)	Phthalate concentration beverage (µg/g)
DBP	180.4	0.0031	500	0.0011
BBP	246	0.0017	500	0.0008
DEHP	9840	0.0025	500	0.0492

The migration factor is varying for the three phthalate types resulting in a large difference of phthalate contents in food and beverages. It is important to note that the migration factor for food is much higher than the migration factor for beverages. Furthermore, since the amount of DEHP in the packaging is much higher than the amount of DBP and BBP the eventual amount of phthalates in the food and beverages are predominantly DEHP.

Dutch consumption data as surveyed by the RIVM (RIVM, 2021) is then used to further calculate the daily intake of phthalates for the Dutch population. The amount of phthalates in food is multiplied by the amount of fatty food (dairy, meat, fish, and oil) consumed in a day by the top 95% of the Dutch population. For beverages the amount of phthalates in beverage is multiplied by the amount of beverage (non-alcoholic and alcoholic) consumed by the top 95% of the Dutch population exact daily consumption can be found in appendix I. This is then added together and divided by the bodyweight which was assumed to be 70 kg. The equation can be found in the methodology. Table 12 shows the results of filling in equation 5.

Table 12: Results calculation of Daily intake of phthalates.

Phthalate	Phthalate concentration in food (µg/g)	Food consumption (g/day)	Phthalate concentration beverage (µg/g)	Beverage consumption (g/day)	Bodyweight (kg_{bw})	Daily intake phthalates (µg/(kg_{bw}* day))
DBP	0.04	1149	0.0011	3857	70	0.73

BBP	0.03	1149	0.0008	3857	70	0.59
DEHP	3.31	1149	0.0492	3857	70	57.08

When looking at table 12 it becomes clear that the daily intake of phthalates resulting from consumption of fatty foods is much higher than the daily intake resulting from beverage consumption, even though the consumption of beverages is about 3 times as high as the consumption of food. Furthermore, it immediately becomes clear that the total daily intake of DEHP is the highest of all three phthalate types, this is mainly due to a higher initial concentration and a higher migration factor.

4.3 Risk.

To easily compare the expected daily intake to the TDI defined in chapter 4.1, the expected daily intake is converted to mg/(kg_{bw}*day). The RQ (Risk Quotient) is then calculated using equation 6, The expected daily intake, the TDI, and the RQ are shown in table 13.

Table 13: The expected daily intake, the tolerable daily intake, and the RQ for the three phthalates.

Phthalate	Daily intake phthalates (mg/(kg_{bw}*day))	TDI (mg/(kg_{bw}*day))	RQ
DBP	0.0007	0.01	0.07
BBP	0.0006	0.5	0.001
DEHP	0.0571	0.05	1.14

Table 13 shows that the risks related to expected DBP and BBP intake remain below the TDI as defined by the EFSA with at least a factor 10 and 100 respectively as shown by the RQ. But, the expected daily intake for DEHP is slightly above the TDI, with a RQ of 1.14, indicating that there could potentially be health risks for the Dutch population due to phthalate exposure resulting from food and beverage consumption from recycled plastic from domestic household waste.

To further assess this risk of phthalate exposure the total daily intake for phthalates as a group is calculated by multiplying the phthalates with the RPFs to get DEHP equivalents. These are then combined to create a potential exposure to the phthalate group. The results are shown in table 14.

Table 14: Results of calculating DEHP equivalents of the phthalate group.

Phthalate	Daily intake phthalates (mg/(kg_{bw}*day))	RPF	Daily intake DEHP equivalents (mg/(kg_{bw}*day))	Total daily intake DEHP equivalents (mg/(kg_{bw}*day))	TDI DEHP equivalents (mg/(kg_{bw}*day))
DBP	0.0007	5	0.0036		
BBP	0.0006	0.1	0.0001	0.061	0.05
DEHP	0.0571	1	0.0571		

For phthalates as a group the total daily intake is above the tolerable daily intake with a RQ of 1.22, indicating that there are risks resulting from in recycled plastic packaged food and beverage consumption. The risks would be related to effects on reproduction, as discussed in chapter 4.1.

4.4 Uncertainties and discussion.

The calculation of potential exposure to DEHP equivalents has shown that there could be risks involved when it comes to consumption from recycled plastic. This calculation does however consist of a few assumptions that might have a large influence on the calculated total daily intake. The assumptions are made to reflect the upper boundary of the risk, the assumptions are listed below.

It is assumed that all food and beverage products are packaged in 100% recycled plastic packaging. This is currently not the case but knowing that the Netherlands is heading towards a circular economy this is a future perspective. In today's economy there is less recycled plastic used in packaging and there are alternatives to plastic as well (glass, cardboard, cans) so, the fact that there is less recycled plastic in might result in overestimation of the expected daily intake.

The worst-case scenario is taken for the initial amount of phthalates present in the recycled plastic. The upper limits as found by Pivnenko et al. (2016) are taken, this means that for this calculation all recycled plastic packaging would contain this upper limit. In reality the average amount of phthalates in recycled plastic is probably lower resulting in an overestimation.

For the consumption data (RIVM, 2021) the upper 95% is taken meaning that somebody would consume a very high amount of different food types and beverages. Actual consumption is often lower than this, resulting in an overestimation.

The migration factor of phthalates from plastic to food depends on many different factors (e.g. the physical properties of the plastic, the physical properties of the product, temperature, and the duration of the contact) (Q. Xu et al., 2010). For the calculation of the potential exposure in this research the migration factor for storage at 20°C for 2 months was used. But if a product were to be stored at a different temperature or for a different duration this affects the migration factor, resulting in either an overestimation or an underestimation, depending on the products and their storage.

The migration factor for oil and mineral water is assumed to be representative for fatty foods and for beverages respectively. But the actual migration factor for these fatty foods and for beverages might be different as their properties can vary per type of food or beverage resulting in an over- or underestimation.

For the expected exposure only beverages have been taken into account for the mineral water migration factor. According to Q. Xu et al. (2010) however, the migration factor for mineral water could also be representative for other, more aqueous foods. Resulting in an underestimation of the potential exposure.

Since there was no data found on DINP presence in recycled plastics, it was excluded from the exposure calculation. But, DINP does have a RPF of 0.3 (EFSA Panel on Food Contact Materials, Enzymes and Processing Aids (CEP) et al., 2019), meaning that it could have an impact on the eventual exposure to DEHP-equivalents. Leading to an underestimation.

In this risk assessment it was not taken into account that phthalates may accumulate if plastics are recycled multiple times but there are no phthalate removal technologies used. The potential for this is highlighted by Eriksen et al. (2018) for heavy metals. Leading to a potential underestimation.

The assumptions made to calculate the potential exposure result in large uncertainties for the expected exposure. The current exposure to phthalates will probably be lower than the calculated exposure, since recycled plastic in contact with food can have a large influence on the calculation. But, as plastic recycling is bound to increase, the amount of recycled plastics in contact with foods shall increase, and the accumulation of phthalates in recycled plastics might increase, thus potential exposure to phthalates will increase, meaning that the potential exposure will approach the calculated exposure in the future. Furthermore, since aqueous foods and DINP were not taken into account in this research, the potential exposure in the future might eventually turn out to be higher than calculated. As it is unknown how much DINP is present in recycled plastics. To further reduce uncertainties further research on the presence of phthalates in recycled plastic after different recycling techniques, further research on migration factors for different food products and plastics is highly recommended, and further research on accumulation of phthalates in recycled plastic through multiple cycles is highly recommended.

Even though there are some uncertainties regarding the calculation of the potential exposure to phthalates from food packaging. The fact that the potential exposure to phthalates via food and beverage consumption from recycled packaging is higher than the TDI as established by the EFSA is a concern. Further research into phthalates in recycled plastic in food contact materials and its origin is strongly suggested.

A shift towards more recycled plastic in food packaging is taking place (European Comission, 2022), so it is becoming more and more important to make sure that recycled plastics pose no danger to human health when used as food packaging. Since the risk assessment indicates that there are potential health risks related to phthalates in plastic recycling, a concern assessment was conducted to see what the perspectives and attitudes of different stakeholders are towards the risks related to additives in recycled plastic for food contact products. An insight into this can be a useful basis for risk management.

5. Concern assessment: additives in recycled plastic.

For the concern assessment each subchapter shall first present the raw data as gained from the deductive analysis of the interviews (for 5.1-5.4), or from the literature study (for 5.4 and 5.5). This data is then interpreted in light of the criterion for societal concern. The assessment shall then be concluded with a discussion and overview of the presence of the different criteria for societal concern.

5.1 Differences in priorities of stakeholders.

During the interviews some clear differences in stakeholder priorities were found. The waste side of the system (the collection company, separation company and recyclers) are mostly focussed on producing a high amount of output material, which results in a larger profit. The collection company states that they must keep in mind their sales department that sets certain standards. The separation company states that they are trying to prioritize quality but are paid for quantity (*separation company*). Recycler 1 states: "The most important is safety of our employees, second is compliance and third is amount of recycled content." And recycler 2 states: "In the end everything depends on the quality we are able to deliver." The goal of the packaging company was more focussed on reducing packaging material whenever it can do so and experiencing as little social backlash (e.g., negative opinions expressed on social media) as possible. They state that: "if the world changes then opinions change, and we try to stay ahead of those changing opinions" Furthermore, the consumer organization prioritizes the environment, and is actively supporting the consumer to purchase more sustainable materials, including recycled plastic (*Consumer organization*).

When asking the different stakeholders what their priorities were a few different views arose. None of the stakeholders mentioned dealing with additives in recycled plastic as a priority. This is mainly caused by the fact that stakeholders are primarily looking at health hazards in their own work place and finances. Since the priorities of the stakeholders differ throughout the system risk management become more complex, the waste side of the system might for example not be in favour of more legislation, as this further complicates their work and reduces the amount of plastic they can legally recycle, resulting in a lower income. The packaging company primarily focuses on avoiding social backlash so it is imaginable that the packaging company would not want potential health risks related to their products to enter public discussions. The consumer organization is largely prioritizing the environment and might thus be in favour of stricter legislation. Risk management should navigate these different priorities carefully to have all stakeholders on board and create consensus about the management strategies. The "differences in priorities of stakeholders" criterion has been determined to be medium since there are no large conflicts in priorities but there are large differences.

5.2 Difference in risk attitudes.

When speaking about risks related to plastic the main risks mentioned were potential health risks. The different stakeholders however, mentioned different origins for these health risks. The collection company for example mentioned the risks related to additives in microplastics in drinking water. They stated that it is not so much about the health effects related to plastics or microplastics. But more about the health effects related to additives present in these plastics, especially since recycling companies create a "cocktail" of different substances. Of which a large part will eventually end up in wastewater, partially due to the washing step at the recyclers. This cocktail of substances can even contain substances that are added to virgin plastics in other countries where legislations are different, resulting in a very complex mixture. And it gets even worse, according to the collection company, this wastewater is not adequately cleaned. Resulting in these toxic additives containing microplastics ending up in surface water, and eventually even in drinking water. They state: “Generally speaking, if you open the tap here or at home, you will always find concentrations of microplastics in drinking water.” (*Collection company*).

The consumer organization also recognizes health and environmental risks related to additives. They mention two kinds of problems. Firstly, there is the problem of environmental risk. Do the additives bring harm to the environment? And secondly, the problem of health risks is of high importance. For phthalates for example, it is known that there are health risks. This is why they are banned from toys. The consumer company states that for producers it would be logical to have as little phthalates as possible in your product. And that the producers are probably replacing phthalates with other plasticizers. (*Consumer organisation*)

One recycler sees health risks related to chemicals. Recycler 2 states that if a recyclable crate leaves the closed loop system, it cannot be used as a food grade material anymore. Because if a crate were to be misused and get contaminated with chemicals or other alarming substances, which would then be very hard to remove during the recycling process. The consumer would as a result be exposed to a health risk. (*Recycler 2*) Recycler 1 states that the laws on recycling from plastic general waste to food-grade materials is very strict, because of the alarming chemicals that could be present in non-food plastic products in the plastic waste. The recycler does state that this is even a bit too strict as the plastic waste goes through an elaborate cleaning process, in which it is extruded twice. They state that you won’t find any of these alarming substances after the recycling process. But rules are rules. Even though there are plenty of researches stating that this law can be less strict. (*Recycler 1*)

The separation company does not mention any specific health risks related to additives or recycling. The packaging producer, interestingly, mentions a different but comparable problem. The packaging producer states that a potential health risk occurs when recycling cardboard for FCM, the contaminants in this case are called MOSH, MOAH. The contaminants originate from mineral oils used for painting cardboard, and research has shown that the MOSH, MOAH contaminants can cause health risks when too much enters the human body (Biedermann & Grob, 2010). The packaging producer states that the migration of MOSH, MOAH into food only occurs for long-lasting packaged products. But more annoyingly, MOSH, MOAH can migrate from a contaminated packaging into a “clean” packaging standing next to it. Because of this, the packaging producer has switched to using virgin cardboard for food packaging. (*Packaging producer*)

When the stakeholders were asked whether they saw any risks related to additives in recycled plastic in food packaging they reacted in a variety of ways, thus indicating a variety of different risk attitudes. The collection company had a very negative attitude towards the health risks related to additives, but not so much from food packaging. They stated that the main concern are risks related to additives in microplastic ending up in drinking water from the tap. The consumer organisation also had a negative attitude towards the health risks related to additives, and more specifically phthalates. But they expressed a trust in production companies to make sure that these harmful phthalates were not present in products anymore. When asking the recyclers about the risks related to additives in recycled plastics, they stated that additives were not a major concern, indicating a neutral attitude towards the risks related to phthalates. Recycler 1 even stated that the legislation was too strict which can be interpreted as having a positive attitude towards the risk (thus not seeing any risks related to additives). The separation company did not see any health risks related to additives in recycled plastic, thus having a positive risk attitude. The packaging producer interestingly mentioned the different but similar topic of MOSH, MOAH as an example. They used this example to illustrate the possible dangers relating to recycling and additives present after recycling, this was thus an indication of a negative risk attitude. Since the attitudes towards the risk were very different for all stakeholders the “difference in risk attitudes” criterion is determined to be high. When managing the risks related to additives in recycled plastic in food contact products it is important to take these different attitudes into account. Some stakeholders may be very willing to help in managing the risks whereas others might not see the necessity of managing the additive problem as in their eyes, there is no risk present.

5.3 Potential for conflict and mobilization.

When asking whether a potential for social conflict was present for plastic recycling the collection company immediately mentioned the BPA discussion[5], and the fact that many packaging now says that products are BPA free. (*Collection company*) The consumer organisation also mentions the BPA discussion, but supplements this with the fact that the same has happened for phthalates. According to the consumer organization the social discussion that is currently being held is about P-fas (*Consumer organization*). The packaging company confirms this, they have had some P-fas discussions recently. The packaging company also states that there is a potential for social conflict for the MOSH/MOAH situation in cardboard if it were to get more publicity. Furthermore, they state: “currently consumers are very anti plastic.” (*Packaging company*). Which the consumer organization also highlights: “The consumer thinks plastic is a bad thing always.” (*Consumer organization*) The packaging organization states that it is important to avoid risks to human health, mainly due to public backlash. And that: “Before there is legislation, you need to have a business policy.” (*Packaging company*)

When asking the stakeholders whether they saw a potential for social conflict and mobilization regarding the additive risk problem. 3 of the 6 stakeholders immediately mentioned social conflicts and mobilization on similar topics that had occurred in the past. These past events are seen as an illustration of the potential for conflict and mobilization for the additive risk problem. The additive risk problem thus scores high on the “potential for conflict and mobilization” criterion as there are examples of similar problems giving rise to conflict and mobilization, like the BPA discussion (Lubitow, 2013). These problems are however only mentioned by stakeholders that are in close contact with consumers and thus the public opinion.

5.4 Spill-over effects.

The main spill-over effect for additives in recycled plastics are the additive containing microplastics ending up in waterbodies as described by the collection company during the interviews. This is also described by Brown et al. (2023). This spill-over effect can cause serious harm to ecosystems, the exact harm this might cause to ecosystems remains unclear to this point (Sridharan et al., 2022), but further research into this is strongly suggested. Besides harm to ecosystems recycler 1 mentions the high usage of water and energy as a problem to recycling. They state that this might become a problem in the future as the news page is already stating problems with water shortages in the summer. The “spill-over effects” criteria is thus determined to be medium, since there are spill-overs into drinking water security and environmental health, but the exact effects remain uncertain.

5.5 Persistence.

The presence of additives in the plastic recycling system can be seen as persistent. Especially since the hazardous contaminants will go through multiple cycles of recycling and thus come into contact with humans more than once. But since plastic cannot be recycled infinitely the additives will at

[5] Bisphenol A, a substance found in a wide variety of products that has light endocrine disrupting effects on humans (Wazir & Mokbel, 2019).

some point leave the plastic recycling system. And if no new harmful additives are introduced to the plastic recycling system the risk will no longer persist, this can however not be done immediately (Leslie et al., 2016). Furthermore, the endocrine disrupting effects of additives (phthalates) can be seen as persistent, since exposure to the toxic substances can lead to reduced reproductive effects, which will have an impact on humans for the rest of their lives. So, the "persistence" criterion is determined to be high.

5.6 Discussion of the societal concern for the additive risk problem.

Looking at the results of the concern assessment it can be stated that the additive risk problem is of a medium to high concern to society. An overview of the presence of the five assessed criteria is shown in table 15 below.

Table 15: Overview of the presence of the societal concern criteria for additives in recycled plastic.

Criteria	Low presence	Medium presence	High presence
Differences in priorities of stakeholders		**X**	
Difference in risk attitudes			**X**
Potential for conflict and mobilization			**X**
Spill-over effects		**X**	
Persistence			**X**

Looking at table 15 the societal concern of the additive risk problem becomes clear. The additive risk problem is of concern to society because it is highly persistent as the hazard has lifelong effects and the exposure pathway cannot be stopped at once. On top of this the risk can spill-over, as additive containing microplastics tend to end up in the natural environment, where they can be harmful to ecosystems (Brown et al., 2023). Furthermore, the problem has a potential to give rise to public conflict and mobilization, past societal conflicts around additives like BPA have shown how a risk like this can be picked up by the public. For this reason, the packaging producer is mentioning that it is important for a company to have its own policy when there is a possibility for social backlash. This can be seen as a form of corporate social responsibility, where the companies try to act in an ethical way to conform with what society would expect from the company (Kiygi-Calli, 2019). These three criteria clearly indicate the importance of managing the risk adequately. But management of the risk can be tedious as the stakeholders in the plastic recycling system tend to have different priorities, and different attitudes towards the risk. The fact that the differing priorities and attitudes are not often directed at the additive risk problem, even though the stakeholders were asked about risks related to additives, shows that there is currently very little awareness of the additive risk problem among stakeholders. Furthermore, different risk attitudes and priorities can make risk management a complicated task. Where some stakeholders would be very much in favour of stricter guidelines others might protest this. A management strategy that is acceptable to all stakeholders must be created to effectively manage the additive risk problem. To do so the risk and concern assessment in this research can serve as a basis.

When interpreting the concern assessment, it should be kept in mind that no retailers and brand-owners were willing to participate in the interviews. This results in a one-sided concern assessment since the waste side of the system is much more represented then the production side of the system. Retailers and brand-owners could have different priorities and attitudes regarding the risk problem, Pålsson & Sandberg (2021) for example found that retailers and brand-owners tend to focus on either the financial or environmental aspects of packaging, this is also shown by the Lidl example mentioned in section 3.3. Furthermore, they might see the potential for social conflict in a very different light since they deal with consumers on a more frequent basis.

Furthermore, it was assumed that the consumer organisation represents all consumers. In reality, consumers can have a very wide variety of opinions on the topic, which could result in more varying priorities and risk attitudes. For the BPA social conflict for example, different groups reacted differently to the discussion, depending on their educational level (Brewer & Ley, 2014).

6. Discussion.

The discussion has been separated into a discussion of methodologies and scope and a discussion of the results.

6.1 Methodologies and scope.

This thesis has assessed barriers and opportunities to increase food-grade recycling for the Dutch plastic recycling system by conducting a literature study, semi-structured interviews, a thematic analysis, a risk assessment, a concern assessment, and a deductive analysis. The research has however been limited by some aspects.

First, since the literature study has been conducted using specific search queries, some sources of information might have remained unfound in this research.

Second, the risk assessment has been conducted to depict a worst-case scenario, which probably resulted in an overestimation of the risk. A description of the assumptions made in the risk assessment has been given in section 4.4.

Third, as discussed in section 5.6, it is important to note that no interviews could be conducted with retailers and business-owners, resulting in a study focused on the waste side of the Dutch plastic recycling system. The thesis does, as a result, give clear insights into the more technical problems at hand, as all stakeholders on the waste side of the system did agree to an interview, resulting in some interesting prospects. But the thesis may miss some important views on the barriers and opportunities from the retail and brand-owner perspective. The separation company for example has stated that the Lidl does have quite a large influence in the plastic recycling system. In further research it could be very interesting to interview this side of the system, as to create further insights into the system.

Fourth, regarding the concern assessment, the "psychological stress and discomfort" criterion was not assessed since the interviewees were asked to answer from the perspective of their organisation and not themselves. No further interviews or surveys with individuals were conducted, since psychological stress and discomfort occurs in the person and not the organisation the criteria could not be assessed. The "inequity and injustice" criterion could not be assessed as no data on plastic usage per socio-economic class could be found for the Netherlands, so, whether there were injustices caused by the risk problem could not be determined.

Finally, for the "potential for conflict and mobilization" criterion, as a supplement to this research, it could be very valuable to do a social media study on the risks related to additives in recycled plastic in food contact products. This might give a more accurate insight into the status of social conflict and mobilization for this risk problem.

Furthermore, regarding the scope of this research, it should be noted that most interviewees are working on plastic recycling and in favour of plastic recycling. Plastic recycling in this research is presented as one of the most important options for a circular economy. But, recycling is an end-of-the-pipe solution (Hutner et al., 2017), recycling is seen as the 9th R for the circular economy framework as described by Kirchherr et al. (2017), indicating that there are many other ways that should be looked at to achieve a circular economy. Calisto Friant et al. (2022) highlight the importance of looking into the reduce, refuse, and reuse side of the system. Plastics, however, have become irreplaceable in today's society (Geyer et al., 2017). Thus, for the plastics that cannot be reduced, refused, or reused, a discussion that this research has not focused on, recycling is still an important step for a more circular economy.

With that in mind this research has found some interesting implications for the future of food-grade plastic recycling from Dutch household waste.

6.2 Results.

This discussion chapter builds upon the earlier discussions held in sections 3.5, 4.4, and 5.6.

With a shift towards a circular economy taking place and higher European recycling targets, the Dutch plastic recycling system needs to change. More recycled product must be used for food packaging since this is 40% of the Dutch plastic use (Verrips et al., 2019). Looking at the Dutch plastic recycling system some interesting prospects for increasing plastic recycling for food-contact material were found. The stakeholders indicated a few barriers which are discussed in section 3.5. The most important barrier was found to be the quality of the waste stream. Thus, to increase plastic recycling for food grade material in the Netherlands, a higher quality plastic waste stream is required. A risk assessment and concern assessment, as suggested by the IRGC, on phthalates and additives in recycled plastic in food contact materials were then applied to generate more insight into why the quality of the waste stream is of importance for plastic recycling.

During the risk assessment it was shown that there are potential health risks associated with food and beverage consumption from recycled plastic packaging containing phthalates. The main health risks were found to be negative effects on reproduction, as phthalates have an endocrine disrupting effect. The potential exposure to phthalates, for the worst-case scenario, as calculated in this research was 0.061mg/(kg_{bw}*day) which is above the tolerable daily intake of 0.05mg/(kg_{bw}*day) determined by the EFSA, with a RQ of 1.22. This RQ was found for the worst-case scenario which assumes high amounts of recycled plastic in food contact materials, as described in section 4.4. Since the Netherlands is aiming to use more recycled plastic in food contact materials, the risks for the Dutch population will grow, as the real life scenario approaches the worst-case scenario. This highlights the importance of a high quality waste stream, as there are many potentially harmful contaminants besides phthalates that could end up in recycled packaging (Shi et al., 2023). The concern assessment was then conducted to assess how concerning the additive risk problem is for Dutch society.

The concern assessment showed that a medium to high societal concern is present for additives in recycled plastics. The most important criteria influencing the societal concern were found to be “difference in risk attitudes”, “potential for conflict and mobilization”, and “persistence”. For the risk attitudes the collection company and consumer organisation appear to be aware of the health risks related to additives in recycled plastics, but the separation company does not see this as a potential problem. The recyclers indicate a different danger, related to chemicals, and the packaging producer highlights problems related to additives in cardboard recycling. There is a large potential for social conflict and mobilization, this is shown by past conflicts on for example BPA (Lubitow, 2013). Furthermore, reproductive health effects are irreversible making the risk problem persistent. The criteria for societal concern for additives in recycled food contact products are discussed in section 5.6. The concern assessment shows that very few stakeholders seem to be working on the additive risk problem, even though there are potential health risks and societal concerns associated with the risk problem.

Besides there being a risk for recycled plastic, the packaging producer indicated that similar risks occur when recycling cardboard for food packaging. For recycled cardboard, contaminants known as MOSH and MOAH tend to migrate into food (Biedermann & Grob, 2010). Indicating that the additive risk problem is not one of a kind, and similar risk problems can occur for other types of recycling for food grade materials. This highlights the importance of accurately dealing with health risks related to migrating substances in recycling. The additive risk problem thus shows that there are problems when recycling for food contact materials that needs to be addressed by risk managers. For the phthalate risk problem specifically, it yet remains unclear where the phthalates found in recycled product originate from (Coniglio et al., 2020; Leslie et al., 2016; Pivnenko et al., 2016; Z. Xu et al., 2020). Further research into this is strongly suggested to create clearer risk management strategies. Risk managers should consider the different perspectives within the Dutch plastic recycling system and look into the suggestions that came to light in section 3.5. The most important suggestions for an improved quality of the plastic waste stream, and thus more and safer food-grade recycling are highlighted below.

Firstly, there is a potential for improved separation at the separation company. The company itself states that they can do much better separation, resulting in a waste stream that can be easier recycled into food grade material. As it aligns better with the 95/5 norm. The separation company however does not see a financial incentive to do so. Indicating that there is a potential to increase food-grade recycling, but research on how to incentivize the separation company is needed. This increase in food-grade recycling, however, does not necessarily mean less additives present in the recycled food grade material. Incentivizing the separation company thus does not necessarily mitigate the phthalate/additive risk problem.

Secondly, an option for a higher quality waste stream was found to be design-for-recycling, as this creates a cleaner waste stream from the start. Design-for-recycling should focus on creating products that are recognized by the separation machinery, creating products using only one material type (preferably PET since this can be recycled for food-grade plastic) and creating products that contain no potentially hazardous additives (elaborately tested additives). If design-for-recycling would take all these factors into account it has a potential to improve the overall quality of the waste stream, reduce the amount of phthalates or other harmful additives in the collection phase, and even reduce costs related to the separation stage. Further research into design-for-recycling is highly recommended.

Lastly, by increasing chemical recycling more recycled food-grade material can be created. Chemical recycling has some advantages but comes at a cost. It should be noted that chemical recycling is more costly than mechanical recycling, but it does create a cleaner product as plastics are reduced to oil. Creating the option to have an additive free recycled product. Chemical recycling thus has a potential as a supplement to mechanical recycling, but, for chemical recycling a quality waste stream is still required.

7. Conclusion.

In conclusion, this thesis provides valuable insights into barriers and opportunities for producing more food grade recycled plastic from household waste in the Netherlands by assessing the risks and concerns related to additives in recycled plastic in food contact material. The risk assessment highlights potential health risks associated with phthalates in recycled plastic in food contact materials. These health risks increase when more recycled plastic is used in food contact materials in comparison with the current situation. The concern assessment shows that the additive risk problem is of concern to society. This is due to differing stakeholder attitudes, as stakeholders are sometimes overlooking risks related to additives in recycled food contact material, as they see other risks like chemicals ending up in recycled product. The potential for social conflict and mobilization, and the persistence of the problem also play a major role in societal concern. Thus, recycling more plastic for food contact materials poses a higher risk to human health, which is of concern to the society. This risk needs to be adequately and carefully managed.

Due to European legislation and a shift to a circular economy the Netherlands will probably need to recycle more plastic for food contact material. To enable increased recycling while safeguarding public health, it is crucial to prioritize improving the quality of the plastic waste stream. The primary barrier identified by stakeholders is the quality of the waste stream itself. Future policies should focus on enhancing waste stream quality rather than solely increasing recycling targets.

Improving the quality of the plastic waste stream in the Netherlands is a complicated task with many different aspects to it. This thesis identified three suggestions to improve the quality of the waste stream that were indicated by the different stakeholders: incentivizing the separation company, adopting design-for-recycling strategies, and chemical recycling. Of the three suggestions design-for-recycling is seen as the most promising as it increases the waste stream quality from an early stage, resulting in system-wide benefits. Further research into all three suggestions is highly recommended, to further inform policy makers for producing more food-grade recycled plastic from household waste in the Netherlands.

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Appendix I – Dutch food and beverage consumption statistics.

Table 16: Upper 95% of Dutch daily food and beverage consumption for adults (RIVM, 2021).

Product	Dutch consumption upper 95% (g/day)
Dairy	809
Meat	206
Fish	88
oil	47
non-alcoholic beverage	3332
alcoholic beverage	525