Bachelor's thesis

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KJ2900 Bachelorprosjekt i kjemi

OPFRs in e-waste plastic: problems and solutions in the circular economy

Bachelor's thesis in chemistry
Supervisor: Hans Peter Arp
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ABSTRACT

After different bans and restrictions of several brominated flame retardants (BFRs) because of their persistent and toxic properties, the use of organophosphate flame retardants (OPFRs) as alternatives have increased. OPFRs were considered a safer group of flame retardants, but later research has shown that some OPFRs also cause severe health risks. The large increase in use of OPFRs is concerning, and one large source of the substances in the environment is the plastic in e-waste. Simultaneously as the use of OPFRs is increasing, the emphasize on a circular economy and waste handling is also growing. This causes a conflict between the favorable closed loop economy and possible toxic compounds like OPFRs having an extended life leading to increase exposure to the environment and humans. The aim of this thesis was therefore to discuss the extent of the problem with OPFRs in e-waste plastic, in addition to proposing some solutions in the circular economy.

Because of the lack of research and knowledge concerning OPFRs in a circular economy perspective, the methodology section of this thesis was restricted to a study proposing an approach to measure OPFRs in e-waste plastic. Problems and solutions were then discussed considering this study and the data gaps that were uncovered. The main findings of this thesis were that the extent of the problem is increased by the measures set for bettering the environment, and that the best solution seems to be preventing OPFRs from entering the closed loop economy. Still, because of the great knowledge and data gaps surrounding both OPFRs and sustainable plastic recycling methods, this though experiment was limited. In conclusion, the lack of information on the topic could be increasing the problem itself, and new research must take place to solve the problem with OPFRs in e-waste plastic in a circular economy perspective.

SAMMENDRAG

Etter ulike forbud og restriksjoner på flere bromerte flammehemmere (BFR) på grunn av deres giftige og persistente egenskaper, har bruken av de alternative fosfororganiske flammehemmerne (OPFR) økt betraktelig. OPFRer ble ansett som en tryggere gruppe flammehemmere, men forskning har vist at også noen av disse forbindelsene medfører alvorlige helseproblemer. Økningen i bruken av OPFRer er derfor bekymringsfull, og en stor kilde til disse i miljøet er plast fra e-avfall. Samtidig som bruken av OPFRer øker, øker også søkelyset på sirkulær økonomi og avfallshåndtering. Dette skaper en konflikt mellom en ønsket lukket økonomi, og mulige giftige forbindelser som OPFRer som har en lang levetid og dermed økende eksponeringen for miljøet og mennesker. Målet med denne oppgaven var derfor å diskutere omfanget av problemet med OPFRer i plast fra e-avfall, i tillegg til å foreslå noen løsninger innen den sirkulære økonomien.

På grunn av mangel på forskning og kunnskap om OPFRer i et sirkulærøkonomiperspektiv, ble metodedelen i denne oppgaven begrenset til en studie som foreslår en tilnærming for å måle OPFRer i plast fra e-avfall. Problemer og løsninger ble deretter diskutert med tanke på denne studien og datamangelen som ble avdekket. Hovedfunnene i denne oppgaven var at omfanget av problemet kan øke på grunn av tiltak som er satt for å bedre miljøet, og at den beste løsningen ser ut til å være å hindre OPFRer fra å komme inn i den lukkede økonomien. Likevel, på grunn av den store kunnskaps- og datamangelen rundt både OPFRer og bærekraftige resirkuleringsmetoder for plast, ble dette tankeeksperimentet begrenset. Konklusjonen er at mangel på informasjon om emnet kan øke problemet i seg selv, og ny forskning må finne sted for å løse problemet med OPFRer i plast fra e-avfall i et sirkulærøkonomiperspektiv.

CONTENTS

ABBREVIATIONS

List of all abbreviations in alphabetic order:

- **BFRs** Brominated Flame retardants
- **DF** Detection Frequency
- **EU** European union
- **EC** European Commission
- **E-waste** Electrical and electronic waste
- **FRs** Flame retardants
- **LRAT** Long-range atmospheric transport
- **NTNU** Norwegian University of Science and Technology
- **OPFRs** organophosphate flame retardants
- **PBDEs** Polybrominated diphenyl ethers
- **PMOCs** persistent mobile organic compounds
- **POPs** Persistant organic pollutants
- **WEEE** Waste electrical and electronic equipment
- **XRF** x-ray fluorescence

CHAPTER

ONE

INTRODUCTION

"Throw-away society", consumer culture and commercialism, all different expressions describing a society where products live short lives and the demand for something new and improved is substantial. Because of this culture, expressions and models like circular economy, waste hierarchy and recycling has been created to reduce waste and pollution. The emphasis on such measures is greater than ever, and both the idea and the intentions are good, but what if it has the opposite effect on the environment? What if recycling and re-using ends up releasing more pollutants and toxins instead of reducing them?

One group of pollutants which have received more attention in recent years is organophosphate flame retardants (OPFRs). These compounds have had increased production and use after the ban and restrictions of brominated flame retardants (BFRs) [1] because they were assumed to be less toxic [2]. In later years OPFRs have proved to be causing health concerns and to be persistent in the environment [3]. More research and data on the health effects from OPFRs exposure is still needed, but some OPFRs have been proven to cause endocrine disruption, neurotoxicity, effects on the immune system and different developmental effects [4]. Because OPFRs are usually mixed into polymers, instead of chemically bonded to them, the risk of the chemicals releasing into the environment is greater [5]. Volatilization, abrasion, and leaching are three different ways OPFRs are released, which can happen during production, use, and/or disposal of products containing the compounds [4], [5]. This means that OPFRs can be released throughout a product's "life", and a longer life can mean greater concentrations of the chemicals in the environment.

In addition to being released during production, use, and disposal, recycling of e-waste has been recognized as a crucial source of OPFRs in the environment [2]. Due to the steady increase in worldwide plastic production, which has surpassed 350 million ton per year [6], the need for an increase in cleaner production and resource efficiency has also occurred [7]. Simultaneously, the demand for reusable and recycled plastic is also increasing, something that fits well with the sustainable circular economy model [6].

Therefore, to achieve a circular economy, recycling of e-waste is necessary [8]. However, it is currently limited due to the presence of toxic additives like OPFRs [8]. Taking all of this into account, this bachelor thesis aims to discuss around the following theme:

OPFRs in e-waste plastic: problems and solutions in the circular economy

This report will start with a background section presenting its key terms. First flame retardants will be presented generally, before OPFRs is introduced as the focus of the thesis. Both characteristics and use as well as occurrence in the environment and specific health risks will be listed. Further, a more in-depth description of circular economy and waste hierarchy will be presented. The main essence of the discussion will be data sets regarding OPFRs in the circular economy, which will be presented in the next section "OPFRs in e-waste plastic". The thesis will then proceed with the discussion section, discussing the key knowledge gaps relating to understanding the problems and solutions to OPFRs in e-waste plastic.

CHAPTER

TWO

THEORY

2.1 Flame retardants

Flame retardants (FRs) are a group of chemicals used to inhibit or suppress the process of combustion in different materials [9]. In other words, the compounds can both provide protection from fire, and increase the escape time if a fire occurs. FRs can therefore be critical for saving lives, preventing injuries, and reducing loss of properties [1]. Additives such as FRs can be utilized in commercial products like furniture, electronics such as televisions and cellphones, and even children's products like car seats and clothing when mixed with resins or polymers [10]. This means that there are FRs all around us, and because of different fire safety standards they are used more and more [11].

Depending on their chemical composition FRs can be divided into three main categories: inorganic, halogenated and organophosphorus-containing FRs [1]. In addition to having the ability to inhibit or suppress fires, some FRs have turned out to have characteristics such as being persistent, bioaccumulative and some even toxic to the environment and/or humans and animals [11]. Polybrominated diphenyl ethers (PBDEs) is an example of a group of halogenated FRs which were considered as persistent organic pollutants (POPs) by the Stockholm convention [12], and therefore was banned or voluntarily phased out by different manufacturers. Since PBDEs were one of the most common FRs before the restrictions were made, it resulted in an increase in different FRs like organophosphate flame retardants (OPFRs) [1].

2.2 Organophosphate flame retardants

OPFRs are a group of compounds used in products like plastics, textiles, and different building materials [9]. In addition to being used as FRs these compounds can also be used as plasticizers [13], that is an even broader use of OPFRs. Just as many other FRs, OPFRs are usually water-soluble and added to, instead of being chemically bound to, the products [14]. As a result, they can easily leach into the environment, and do so through the whole lifetime of the product they are added to [9]. It may therefore be logical to assume that the amount of OPFRs in the environment will increase as the lifetime of the products containing the compounds also increase. One source of contamination and human exposure from OPFRs that has been emphasized by previous studies is from waste handling of e-waste[15]. To meet the fire safety regulations required, compounds such as OPFRs have been added to the plastic casings of electric and electronic products in concentrations up to 10-15% in weight [16]. In addition, the use of OPFRs have increased significantly after the phase out of BFRs [1].

The effects of both environmental and human exposure to OPFRs are less well-known than the effects of BFRs, because of lack of studies focusing on the compounds [1]. Still, an increasing interest in OPFRs have occurred in recent years. The concerns with OPFRs are both their persistence and toxicity in the environment, in humans and other organisms. In later years OPFRs have been detected in off-source areas like the Artic and the Antarctic, where persistence and long-range atmospheric transport (LRAT) have been pointed to as the reason [17]. Because of the large volumes being used and the current exposer levels of OPFRs, research has also shown that the compounds potentially cause harm to humans, and especially to children [3]. Furthermore, studies have shown that different OPFRs have potential for endocrine disruption, some are neurotoxic, they can have effects on the immune system, different developmental effects [4] and some are even carcinogenic [11]. This is why OPFRs likely are a regrettable substitute for BFRs [3]. Similar to BFRs, additives like OPFRs are also a problem when they enter the circular economy [8].

2.3 Circular economy

The concept of a circular economy, which has been growing since the late 70s, has gotten considerably more attention in recent years [18]. One way of describing the term is by defining its antonym, "a linear economy". A linear economy describes the process of converting natural resources through production into waste [19], resulting in a significant depletion of the earth's finite resources and a substantial amount of waste. The goal of a circular economy is therefore to create a closed loop system that eliminates the need for resource input and completely halts the generation of waste [18]. With e-waste being a contestant for the fastest growing solid waste stream in the world [19], it is crucial to consider its impact on the circular economy. Since only 5-10% of the plastic produced in the world is recycled, different programs and initiatives are designing and actively promoting new recycling goals for the upcoming years [6]. Simultaneously, due to the abundance of OPFRs and other additives present in electronic waste plastics, and their potential persistence and toxicity, various measures to limit their use are regularly updated [8]. Despite these efforts, there is a concern that the circular economy market, in addition to new recycling goals, may exceed the established guidelines and regulations set for compounds like OPFRs. This can lead to recycling e-waste plastics containing additives like OPFRs, which could result in their introduction into new products.

2.4 Waste hierarchy

The waste hierarchy, which is a tool applied by the European Commission's (EC) Waste Framework [20], suggests a prioritized order from "prevention" at the top and "disposal" at the bottom, for how waste is managed. There are five steps in the waste hierarchy that this thesis operates with, seen in Fig. 2.4.1. The top and most favorable measure of the hierarchy is "prevention", which is also a "non-waste" option [21]. The purpose of "prevention" can be divided into two categories, quantitative and qualitative waste prevention [22]. Quantitative waste prevention means to reduce the total amount of waste, whereas qualitative waste prevention means to reduce harmful substances in different products and materials. The next measure in the waste hierarchy is "reuse", or "preparing for reuse" as in the EC's Waste Framework [20]. Both formulations describe using something more than once, with the key difference being that "preparing for reuse" describes waste that needs adjustments before it can be reused, whereas "reuse" itself is a "non-waste" option [22]. "Recycling" is the third measure in the hierarchy and describes a recovery operation, where waste is reprocessed for either the original or another purpose. This measure does not include energy recovery or when waste is reprocessed and used for fuel or backfilling purposes, which, among other things, goes under the second to last measure "recovery" [20]. The last and least favorable measure in the waste hierarchy is "disposal". Everything that doesn't meet the criteria for "recovery" goes into this category [22], which should be avoided. There are criticisms to both the formulation and the recommendations of the waste hierarchy [21], especially the one described by the EC's Waste Framework, but this thesis will not go further into that discussion.

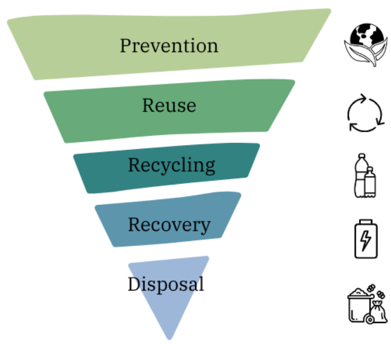

Figure 2.4.1: Waste hierarchy inspired by [21].

CHAPTER
THREE

OPFRS IN E-WASTE PLASTIC

Electrical and electronic waste (e-waste), sometimes called waste electrical and electronic equipment (WEEE), has been acknowledged as a significant contributor of OPFRs to the environment [2]. One reason for this conclusion is the increasingly shorter life cycles of electronic products, from use to disposal, something that contradicts with the principles of the closed loop in a circular economy. Another potential essential source of OPFRs to the environment is informal handling of e-waste [16]. The global plastic production is presently surpassing 350 million tonnes per year [6], and even though e-waste accounts for merely 2% by weight of the overall solid waste stream, it can comprise as much as 70% of hazardous waste that is dumped in landfills [8]. In addition, OPFRs have proven to be anywhere between 5-30% by weight of additives used in the plastic in e-waste. The problem arises when a circular economy aims to reuse and recycle this plastic but are limited by the presence of toxic additives like OPFRs.

There are only few studies that have looked at OPFRs in e-waste plastic, due to a lack of methods to measure this analytically, and the OPFRs composition generally not being reported by manufacturers. A recent method that developed an approach to measuring OPFRs in e-waste plastic is the recent study poster titled "Supercritical fluid chromatography coupled to MS/MS for the analysis of Organophosphate flame retardants (OPFRs)" written by Castro et al. [23]. The data most relevant from this study are the concentrations of 16 different OPFRs in 15 types of WEEE plastic samples, in addition to the proposed pyrolysis at 800ºC as an alternative treatment of the e-waste plastics. As this study is one of the first measurements of OPFRs in e-waste plastic, the discussion section will be mostly based on the data from the poster. It should be emphasized again that data on OPFRs in the circular economy available is lacking, and the thesis is therefore based on the limited existing data. To supplement the data collected from the poster, various online databases were searched using keywords such as "OPFRs", "plastic", "e-waste" and "circular economy". Using these databases allowed for gathering of additional publications relevant to the research project.

The e-waste plastic samples used for the study by Castro et al. was collected from Norway, with some of them being different plastic types and in different waste categories. The concentration of OPFRs in the samples varied from 176-610 000 ng/g, with mixed grinds and pellets being the plastic types with the highest total concentration. Six of the samples had a total concertation >1000 ng/n, mostly the ones with the plastic type PET, PE, or PP. TPhP and TCIPP was the OPFRs presenting the highest concentrations with a concentration range and detection frequency (DF) of respectively 35-279 000 ng/g, 87% and 159-61 800 ng/g, 80%. Three of the OPFRs had a DF of 0%, while the rest varied from 13-93%. The study acknowledges the same problem as in the previous paragraph, that there are no sustainable recycling methods for the e-waste plastic and one of the reasons is the high concentrations of components like OPFRs [23]. One solution presented by the study is treatment of the materials in the form of pyrolysis at 800ºC. This is done to remove OPFRs and preventing them leaching into the environment. The method managed to remove more than 99% of OPFRs and can therefore be a decent option of treatment.

CHAPTER

FOUR

DISCUSSION

In this discussion section findings from the presented study will be interpreted in light of problems and solutions to OPFRs in e-waste plastic seen in the perspective of circular economy strategies. As presented in both the background and methodology section of this thesis, research indicates that OPFRs in e-waste plastic are an increasing problem that needs solutions. This section will therefore be divided into two parts. First, based on the study by Castro et al. [23] in addition to other relevant literature, the extent of the problem will be discussed. What are the concerns and different aspects of the problem? Further, some solutions in the circular economy will be presented and discussed considering the literature. The structure of this part will be based on the different steps of the waste hierarchy presented in the background section. Lastly, limitations of this study will be discussed and suggestions for future research will be presented.

4.1 The extent of the OPFRs in e-waste problem

The result from the presented study indicates that OPFRs are widespread in e-waste plastic [23]. As presented in the background section of this thesis, that is concerning in relation to their possible persistence and toxicity. In the background section of the study, they start with claiming that there are no sustainable recycling methods for e-waste. If that statement holds, it will indicate that the problem with OPFRs in e-waste is of significant extent. The same problem is indicated by several studies that emphasizes informal and primitive e-waste processing as a considerable source of OPFRs [2], [15], [16], [24]. One reason for this may be because of the electronic industries large and rapid growth [25], that can make sustainable waste management unable to keep up with all the waste that is produced. In a journal written by Tullo he discusses “the dysfunction of plastic recycling” [26]. Statistics presented from the US Environmental Protection Agency showed a considerably less recycling rate of plastic compared to paper, metal, and glass. Plastic being technically difficult to recycle was pointed to as one of the reasons, in addition consumers being the reason for assorted waste and lack of methods for recycling many plastic types [26]. Additionally, the methods used today for recycling of plastic rarely account for removal of OPFRs or other hazardous substances, which causes a grater emission of OPFRs in the environment.

On one side, the attention on recycling and other sustainable measures is only increasing with the increasing amount of plastic produced globally [6]. For example, countries like USA through the American Chemistry Council Plastic Division and the members of the European Union (EU) through the union itself have set different recycling goals for plastic packaging for the next two to twenty years. The EC also published their first circular economy action plan in 2015, that possibly influenced several support studies and EU documents the following years [8]. On the other side, a significant proportion of the e-waste produced in high-income countries has been and is still being exported for handling in low- and moderate-income countries [16]. Most of the research done on OPFRs and other possible toxic compounds emitted from bad e-waste handling is therefore done in these countries. It is assumed that approximately 90% of the recycling and disposal done in low-income countries are done by informal sector workers, with open burning, acid leaching, and heating of the e-waste as examples on techniques used. This export of e-waste from high- to low-income countries are often done illegally under the disguise of "recycling" [25], but is also exported for environmental and economic reasons [16]. All of this indicates that regulations and goals set for e-waste handling and a circular economy in typically western countries will have less effect than presumed. When such a substantial amount of the waste is being exported and handled by low-income countries, they may lack the same regulations and emphasis on e-waste in the circular economy.

Another problem pointed out by Castro et al. is based on is that there is no developed analyzing methods for characterizing the residues of the e-waste [23]. Without identifying the specific chemical components of the waste, it can be more difficult to find the best method of disposal or treatment. Additionally, it can be challenging to set appropriate regulations and guidelines for the handling and disposal of the waste without knowing the composition of it. A similar perspective is introduced by Khan [27]. After the Basel convention in 1989 there was only an increase in the export of toxic waste to developing countries even though the convention had the intention of the opposite. This can be explained by the lack of appropriate regulations for handling e-waste, which again can be traced back to lacking knowledge of what possible toxic compounds e-waste contain. That indicates that without complete documentation of the potentially hazardous chemicals in the plastic in e-waste, it can be difficult to handle e-waste plastic in the circular economy [6].

Another aspect of the problem with OPFRs in e-waste plastic is the circular economy perspective itself. The challenge with implementing circular economy principles to handling of e-waste is when the waste consisting of plastic contain hazardous substances like OPFRs. As stated in the background section, the attention on circular economy and recycling measures have only been increasing. But because the different programs and initiatives supporting the circular economy cannot keep up with the research done on substances like OPFRs [8], these toxic substances end up in the closed loop system meant for bettering the environment. On one side, a circular economy is an important and necessary step for reducing waste and the use of earths finite resources. On the other side, a circular economy has the possibility to increase the amount of OPFRs leaching into the environment by extending the products lifetime. The EC's regulation on Ecodesign requirements for electronic displays aimed to prevent this, the accumulation of substances like OPFRS in the waste stream that is the closed loop [8]. Even if there was a completely closed circular economy because of reuse and recycling, without addressing the presence of OPFRs, the substances would likely accumulate in the cycle [28]. This could cause exposure risks in products labeled "recycled" and that are supposedly "good" for the environment.

All these concerns show the problems several different aspects. Firstly, the amount of electrical and electronic products being produced globally causes a problem with the lack of resources and information on how to handle the waste. Further, this can be one of the reasons why high-income countries, which have the highest production and use of these products, export their waste to countries with less restrictions and resources to handle the waste in a sustainable way. Secondly, a circular economy program has the possibility to create more harm than good when it comes to keeping possible toxic compounds like OPFRs from leaching into the environment. This indicates that the benefits of circular economy approach are weakened by the presence of OPFRs in e-waste plastic.

4.2 Solutions to OPFR in e-waste

The aim of this part of the discussion is to find solutions by examining each step of the waste hierarchy presented in the background section. The thesis will start by considering the typically "most favorable" step, "prevention". The discussion will then continue down the pyramid of Fig. 2.4.1., evaluating each step based on relevant literature.

Application of the waste hierarchy

4.2.1 Prevention

Based on what was discussed in the problem section, it might seem like both quantitative and qualitative prevention can be part of the solution. By reducing the total amount of waste, as suggested in quantitative prevention, less e-waste with OPFRs will be circulating in the circular economy loop, and less of the compounds will enter the environment. Also relevant to the problem is the qualitative prevention that emphasize reducing the harmful substances in waste. There are several different aspects to this solution. The most drastically solution would be to stop using OPFRs in electrical and electronic products all together. As presented in the background section, the increase in use of OPFRs came mostly after the bans and restrictions of PBDEs as FRs. Blum et al. claims that because use and reuse of the banned products with PBDEs are leading to long-term exposure of the chemicals, use of alternatives like OPFRs should be avoided [3]. Since research on OPFRs are still limited even after several years of use, that would indicate that OPFRs was likely a regrettable substitution for PBDEs, and maybe should be cut out completely.

Another solution that relates to qualitative prevention is to reduce the amount of OPFRs used in electrical and electronic products, not cut them out entirely. Barouta et al. writes that controlling the application of hazardous substances can be a measure used to prevent accumulation of substances like OPFRs in waste streams [8]. By controlling the use of OPFRs from the production stage, less of the substances will end up leaching into the environment, even with a longer lifetime because of a closed loop system. Statistics from the National Safety Council show that fire deaths in the United States decreased greatly from 1977 to 2021 [29]. This indicates that there are a considerably less amount of death by fires today than 50 years ago, and maybe the need for flame retardants isn't as big as before. This claim will need a greater amount of research before being near concluding, but it can be an argument for reducing the use of toxic FRs. If the harmful effects of OPFRs are greater than the benefits of them as FRs, then maybe a reduce of use would be the best option. Either way, trying to keep possible toxic OPFRs out of the products would be favorable in a circular economy approach [7].

In addition to reducing the use of OPFRs or stop using them all together, another solution could be to limit the use to the least toxic and persistent types of OPFRs. When writing about OPFRs as a possible regrettable substitution for PBDEs, Blum et al. lists chlorinated OPFRs as an especially regrettable alternative [3]. OPFRs, and especially the chlorinated ones, are more suitable for LRAT. Additionally, chlorinated OPFRs are considered as persistent mobile organic compounds (PMOCs) [3]. On one hand, this solution will achieve that the most persistent, and maybe also most toxic, OPFRs are reduced from the plastic in e-waste. Logically this will reduce some of the unwanted effects in both the environment and humans, because the worst OPFRs would be removed from the e-waste plastic. On the other hand, the use of OPFRs would not be reduced in total. This would mean that the occurrence of unwanted effects could still occur, and the problem with OPFRs in the circular economy would not be avoided completely.

4.2.2 Reuse

The next measure of the waste hierarchy is reuse, meaning using the products containing OPFRs more than ones to keep them in the circular economy loop. On one side, reuse is a preferrable "non-waste" option that fits great into the circular economy model [21]. Using electrical and electronic products containing OPFRs more than ones could both be beneficial in an economic and environmental perspective, in the sense that it can generate less production of new products. On the other side, keeping electronics that contain OPFRs in the loop for longer will only increase the amount of the possible toxic compounds leaching into the environment. Without reducing the amount of OPFRs in e-waste already in the production stage, the possible negative effects of the compounds will probably not increase. At least the products with the highest exposure or leakage should be removed from the circular economy rather than being reused. Still, an analysis of the tradeoff between the positives of reusing, like climate benefits, versus the possibility for a greater amount of OPFRs leaching into the environment, should be done. Nevertheless, this indicates that reuse would not be a preferable solution to the problem discussed in this thesis.

4.2.3 Recycling

Recycling is the third measure in the hierarchy and is a recovery operation where the e-waste is reprocessed for either the original or another purpose. As suggested in the problem section of this discussion, all recycling does not have benefitable results to the environment. Wang et al. presents results similar to multiple sources presented earlier, that primitive recycling contributes to the release of OPFRs [30]. Further, a possible solution is presented based on the results of the study, that when recycling workshops are organized and planned, they can help reduce the environmental release of OPFRs instead of increasing them [30]. Another solution could be to remove OPFRs from the e-waste plastic when the products are reprocessed, so that they are removed from the closed loop that is the circular economy. This would both keep the benefits of recycling, in addition to reduce OPFRs possible leaching into the environment. Because of the limited research and analyzing methods developed for OPFRs, there is a need for much more knowledge before this would be a realistic solution. Still, this is just another argument for increasing the research on OPFRs.

A recent development in plastics recycling is sorting technology [31], which could be a possible solution for OPFRs in e-waste plastic. An example is using x-ray fluorescence (XRF) sensors to separate plastics, and possibly sorting out the products containing OPFRs and similar compounds containing phosphorous. These methods still need developing but will be a good recycling alternative in the future. Another solution based on sorting technology is sorting out plastic with low or high OPFRs content by labelling the products as recyclable or not. One type of labeling that have been suggested but not developed is fluorescent labeling [32]. Sorting based on labeling would both help with the demand for more efficient sorting and could also be a good method for sorting out plastic containing OPFRs.

4.2.4 Recovery

The second to last measure entails, among other things, using e-waste for energy recovery. As presented from the data collected in the methodology section, treatment of e-waste plastic in the form of pyrolysis at 800ºC removed more than 99% of OPFRs [23]. Li et al. presents a similar result, that open burning with temperatures from 800-1350ºC lead to high OPFRs destruction efficiencies [2]. On one hand, this would prevent OPFRs entering the circular economy loop while simultaneously achieving energy recovery. If OPFRs in e-waste isn't prevented and there are no good recycling methods for these products, then pyrolysis could be a good alternative for preventing OPFRs leaching into the environment. On the other hand, pyrolysis wouldn't be the best option for the circular economy of plastics. Thermal decomposition of e-waste would mean turning them into less-valuable products. However, pyrolysis can lead to partial recycling, even though it is not a technology available in a large scale today [26]. Chemical pyrolysis has the possibility of being recycled as new chemicals, in addition to mixed plastic types being turned into naphtha which in turn can be broken down into petrochemicals and plastics. This would make it a recovery a descent solution to OPFRs in e-waste plastic. Still, to this date this is not a technology available in a large scale, and pyrolysis technology needs further development before a solution [26].

4.2.5 Disposal

The last and least favorable option in the waste hierarchy is disposal, which in this case means to let e-waste containing OPFRs end up in landfills and e-waste disposal sites. Disposal is usually associated with the worst waste handling option and is not a good solution in a circular economy perspective. This measure is associated with emission of OPFRs to the environment by several different studies [33, 34, 35]. OPFRs are then found in soil, dust, water and humans through the food chain and inhalation. Disposal of e-waste plastic containing OPFRs is therefore not a solution in the circular economy, both because of the amount emitted to the environment and the lack of use of resources.

CHAPTER

FIVE

CONCLUSIONS

The aim of this thesis was to discuss the extent of the problem with OPFRs in e-waste plastic, in addition to proposing some solutions in the circular economy. In summary, the main findings of the study were that measures set to improve the environment, such as the circular economy and the waste hierarchy, do not always match with e-waste plastic containing OPFRs. Problems like current recycling methods struggling to keep up with the amount of e-waste produced, e-waste being sent to countries where there is lack of good waste management infrastructure, and lack of methods to identify and handle OPFRs in e-waste, conflicts with a closed loop economy. Additionally, it is not always the methods that are most favorable from the waste hierarchy that are the best solution for OPFRs in e-waste. Without methods for removing OPFRs from products before they are reused and recycled, the measures will only increase the amount leaching into the environment. Still, prevention, the top measure of the hierarchy, seems to be the best option for reducing the exposure of OPFRs.

A problem that arose repeatedly throughout the thesis, was the extent of the knowledge and data gaps concerning OPFRs in e-waste plastic. These gaps are both limiting the solutions and expanding the problems with the possible toxic and persistent compounds entering the circular economy. Firstly, there is still a limited amount of research and knowledge about OPFRs. More information about the effects of the compounds in addition to analytical methods for determining and measuring the amount of OPFRs in plastic, is necessary to further develop this study. Additionally, there is a knowledge gap for how to recycle and handle plastic waste in general, especially regarding plastic containing possible toxic substances like OPFRs. This should be topics for future research. Nevertheless, preventing OPFRs in e-waste plastic from entering the circular economy is a necessary precaution to protect both humans and the environment from an increased exposure. But by filling the knowledge and data gaps, one will be several steps closer to merge the two goals of a closed loop economy and reduced emissions of OPFRs.

REFERENCES

[1] Ioanna Pantelaki and Dimitra Voutsa. “Organophosphate flame retardants (OPFRs): A review on analytical methods and occurrence in wastewater and aquatic environment”. In: *Science of the Total Environment* 649 (Feb. 2019), pp. 247–263. ISSN: 18791026. DOI: 10.1016/J.SCITOTENV.2018.08.286.

[2] Ting Yu Li et al. “Organophosphate flame retardants emitted from thermal treatment and open burning of e-waste”. In: *Journal of Hazardous Materials* 367 (Apr. 2019), pp. 390–396. ISSN: 18733336. DOI: 10.1016/J.JHAZMAT.2018.12.041.

[3] Arlene Blum et al. “Organophosphate Ester Flame Retardants: Are They a Regrettable Substitution for Polybrominated Diphenyl Ethers?” In: (2019). DOI: 10.1021/acs.estlett.9b00582. URL: https://www.epa.gov/chemical-data-reporting.

[4] Chi Yao, Hanpei Yang, and Ying Li. “A review on organophosphate flame retardants in the environment: Occurrence, accumulation, metabolism and toxicity”. In: *Science of the Total Environment* 795 (Nov. 2021). ISSN: 18791026. DOI: 10.1016/J.SCITOTENV.2021.148837.

[5] Chun Tao He et al. “Occurrence of organophosphorus flame retardants in indoor dust in multiple microenvironments of southern China and implications for human exposure”. In: *Chemosphere* 133 (Aug. 2015), pp. 47–52. ISSN: 18791298. DOI: 10.1016/J.CHEMOSPHERE.2015.03.043.

[6] Leah Chibwe et al. “Target and Nontarget Screening of Organic Chemicals and Metals in Recycled Plastic Materials”. In: (). DOI: 10.1021/acs.est.2c07254. URL: https://doi.org/10.1021/acs.est.2c07254.

[7] H. A. Leslie et al. “Propelling plastics into the circular economy — weeding out the toxics first”. In: *Environment International* 94 (Sept. 2016), pp. 230–234. ISSN: 0160-4120. DOI: 10.1016/J.ENVINT.2016.05.012.

[8] Despoina Barouta et al. “E-plastics in a circular economy: A comprehensive regulatory review”. In: *Journal of Cleaner Production* 355 (June 2022). ISSN: 09596526. DOI: 10.1016/J.JCLEPRO.2022.131711.

[9] Anneli Marklund, Barbro Andersson, and Peter Haglund. "Screening of organophosphorus compounds and their distribution in various indoor environments". In: *Chemosphere* 53.9 (2003), pp. 1137–1146. ISSN: 00456535. DOI: 10.1016/S0045-6535(03)00666-0.

[10] Heather M. Stapleton et al. "Detection of Organophosphate Flame Retardants in Furniture Foam". In: *Environmental Science & Technology* 43.19 (2009), pp. 7490–7495. DOI: 10.1021/es9014019. URL: https://pubs.acs.org/sharingguidelines.

[11] Ike van der Veen and Jacob de Boer. "Phosphorus flame retardants: Properties, production, environmental occurrence, toxicity and analysis". In: *Chemosphere* 88.10 (2012), pp. 1119–1153. ISSN: 18791298. DOI: 10.1016/J.CHEMOSPHERE.2012.03.067.

[12] *Stockholm Convention - Home page.* URL: http://chm.pops.int/.

[13] Kate Hoffman et al. "Temporal Trends in Exposure to Organophosphate Flame Retardants in the United States". In: (2017). DOI: 10.1021/acs.estlett.6b00475. URL: https://pubs.acs.org/sharingguidelines.

[14] Jun Li et al. "Occurrence of organophosphate flame retardants in drinking water from China". In: *Water Research* 54 (May 2014), pp. 53–61. ISSN: 18792448. DOI: 10.1016/J.WATRES.2014.01.031.

[15] Anh Quoc Hoang et al. "Comprehensive characterization of halogenated flame retardants and organophosphate esters in settled dust from informal e-waste and end-of-life vehicle processing sites in Vietnam: Occurrence, source estimation, and risk assessment". In: *Environmental Pollution* 310 (Oct. 2022). ISSN: 18736424. DOI: 10.1016/J.ENVPOL.2022.119809.

[16] Yulong Ma et al. "Human exposure to halogenated and organophosphate flame retardants through informal e-waste handling activities - A critical review". In: *Environmental Pollution* 268 (Jan. 2021). ISSN: 18736424. DOI: 10.1016/J.ENVPOL.2020.115727.

[17] Gao Ling Wei et al. "Organophosphorus flame retardants and plasticizers: Sources, occurrence, toxicity and human exposure". In: *Environmental Pollution* 196 (Jan. 2015), pp. 29–46. ISSN: 0269-7491. DOI: 10.1016/J.ENVPOL.2014.09.012.

[18] Martin Geissdoerfer et al. "The Circular Economy – A new sustainability paradigm?" In: *Journal of Cleaner Production* 143 (Feb. 2017), pp. 757–768. ISSN: 09596526. DOI: 10.1016/J.JCLEPRO.2016.12.048.

[19] Diyasha Sengupta et al. "Circular economy and household e-waste management in India: Integration of formal and informal sectors". In: *Minerals Engineering* 184 (June 2022). ISSN: 08926875. DOI: 10.1016/J.MINENG.2022.107661.

[20] "DIRECTIVE 2008/98/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 19 November 2008 on waste and repealing certain Directives (Text with EEA relevance)". In: ().

[21] Mangesh Gharfalkar et al. "Analysis of waste hierarchy in the European waste directive 2008/98/EC". In: *Waste Management* 39 (May 2015), pp. 305–313. ISSN: 0956-053X. DOI: 10.1016/J.WASMAN.2015.02.007.

[22] "EUROPEAN COMMISSION DIRECTORATE-GENERAL ENVIRONMENT". In: (). URL: http://eur-lex.europa.eu/RECH_consolidated.do..

[23] Gabriela Castro et al. "PosterNordic23_GabrielaCastro (1)". In: ().

[24] Shao-You Lu et al. "Effect of E-waste Recycling on Urinary Metabolites of Organophosphate Flame Retardants and Plasticizers and Their Association with Oxidative Stress". In: (2017). DOI: 10.1021/acs.est.6b05462. URL: https://pubs.acs.org/sharingguidelines.

[25] Xinhui Bi et al. "The major components of particles emitted during recycling of waste printed circuit boards in a typical e-waste workshop of South China". In: *Atmospheric Environment* 44.35 (Nov. 2010), pp. 4440–4445. ISSN: 13522310. DOI: 10.1016/J.ATMOSENV.2010.07.040.

[26] Alexander H. Tullo. "Plastic has a problem; is chemistry the solution?" In: *C&EN Global Enterprise* 97.39 (Oct. 2019), pp. 29–34. ISSN: 2474-7408. DOI: 10.1021/CEN-09739-COVER.

[27] Sabaa Ahmad Khan. "E-products, E-waste and the Basel convention: Regulatory challenges and impossibilities of international environmental law". In: *Review of European, Comparative and International Environmental Law* 25.2 (July 2016), pp. 248–260. ISSN: 20500394. DOI: 10.1111/REEL.12163.

[28] European Union. "Chemicals and the circular economy". In: *HBM4EU the European Human Biomonitoring Initiative* (2022), pp. 1–35. URL: https://www.hbm4eu.eu/wp-content/uploads/2022/07/ChemicalsCircularEconomy.pdf.

[29] *Fire-related Deaths & Injuries - Injury Facts*. URL: https://injuryfacts.nsc.org/home-and-community/safety-topics/fire-related-fatalities-and-injuries/.

[30] Yu Wang et al. "Occurrence and distribution of organophosphate flame retardants (OPFRs) in soil and outdoor settled dust from a multi-waste recycling area in China". In: *Science of the Total Environment* 625 (June 2018), pp. 1056–1064. ISSN: 18791026. DOI: 10.1016/J.SCITOTENV.2018.01.013.

[31] Veena Sahajwalla and Vaibhav Gaikwad. "The present and future of e-waste plastics recycling". In: *Current Opinion in Green and Sustainable Chemistry* 13 (Oct. 2018), pp. 102–107. ISSN: 24522236. DOI: 10.1016/J.COGSC.2018.06.006.

[32] Guojun Gao et al. "REVIEW 1600033 (1 of 26) Up-Conversion Fluorescent Labels for Plastic Recycling: A Review". In: (2017). DOI: 10.1002/adsu.201600033. URL: https://onlinelibrary.wiley.com/doi/10.1002/adsu.201600033.

[33] Joyce Cristale et al. “Occurrence of flame retardants in landfills: A case study in Brazil”. In: *Environmental Research* 168 (Jan. 2019), pp. 420–427. ISSN: 10960953. DOI: 10.1016/J.ENVRES.2018.10.010.

[34] Jiawen Yang et al. “OPFRs in e-waste sites: Integrating in silico approaches, selective bioremediation, and health risk management of residents surrounding”. In: *Journal of Hazardous Materials* 429 (May 2022). ISSN: 18733336. DOI: 10.1016/J.JHAZMAT.2022.128304.

[35] Chiara Frazzoli et al. “E-WASTE threatens health: The scientific solution adopts the one health strategy”. In: *Environmental Research* 212 (Sept. 2022), p. 113227. ISSN: 00139351. DOI: 10.1016/J.ENVRES.2022.113227. URL: https://linkinghub.elsevier.com/retrieve/pii/S0013935122005540.

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