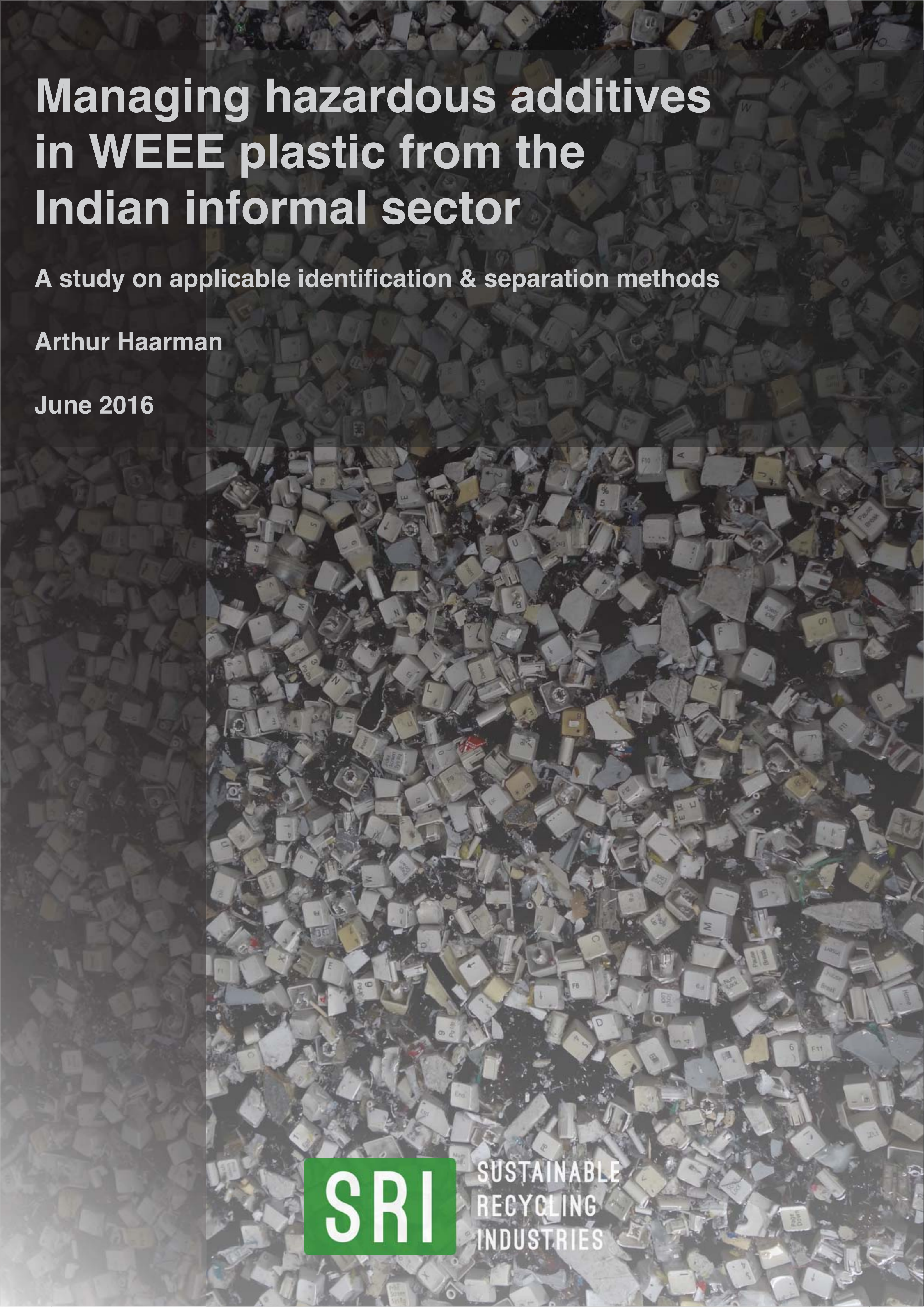

Managing hazardous additives in WEEE plastic from the Indian informal sector

A study on applicable identification & separation methods

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EXECUTIVE SUMMARY

Plastic housings from waste electrical and electronic equipment (WEEE housings) contain hazardous substances such as heavy metals and certain brominated flame retardants (BFRs). The Stockholm convention and national RoHS legislations severely restrict their further use in products. In many cases these plastics should thus not be recycled but safely disposed. In India, a majority of plastics is recycled in informal businesses, which characteristically do not follow work and environmental safety requirements, are not registered with the responsible government bodies, and do not pay taxes. Informal businesses are not limited by any laws and as such try to recycle as much material as possible. Plastics containing hazardous additives are thus reprocessed in unsafe working conditions and re-enter products without any control. This endangers workers and the public and leads to environmental contamination. Approaches of forceful formalisation and compliance with regulations have been tried widely but have mostly remained unsuccessful. Integrative approaches are far more likely to have a lasting impact. In the case of plastic recycling, this requires that the informal sector is given the technical capability and a targeted incentive system for not recycling certain materials in order to “clean the loop”. The first step towards this alternative system is the development of effective methods to identify and separate BFR plastics.

In this context, this study aimed at answering the following questions: Which hazardous additives limit the recycling of high-quality plastics from e-waste such as housings? How can plastics containing these additives be identified and segregated in informal recycling units such as found in India? To answer these guiding questions, desk research and visits in Swiss and Indian WEEE recycling facilities were undertaken to identify possible technologies to identify and separate housing plastics containing hazardous materials. Several months were spent in Delhi to understand the informal plastic recycling system and assess the current fate hazardous plastics. Samples were taken from the informal sector. Pre-selected separation methods considered as applicable in the informal sector were tested to assess their removal efficiency.

Results indicate that the occurrence of hazardous additives varies greatly among different applications. E-waste housings generally do not contain heavy metals in harmful concentrations. Brominated flame retardants occur however in harmful concentrations, especially in some hotspots such as CRT casings. Both findings are in line with measurements conducted in Europe, with the exception that BFR concentrations in India are generally higher. This may be due to longer equipment lifetimes and later introduction of regulations on BFRs in India, which keep substances in circulation.

All observed or tested methods to separate BFR plastics had a high efficiency and were easy to apply. Of the surveyed methods, only density separation should be encouraged due to health concerns with the other methods. This method was shown to have a removal efficiency of above 95%, and 100% of the “clean” fraction (i.e., floating) complies with European standards for depollution of WEEE plastics, allowing these materials to be used in high-quality manufacturing.

Density separation is already used in the informal sector in addition to a plethora of simple and cost effective methods to segregate plastics. The introduction of density operations following detailed instructions with efficiencies verified in this study should thus be possible with a manageable effort. Informal actors in the recycling chains of developing and emerging countries already play an irreplaceable role in achieving high recycling rates. With some limited changes along the recycling chain, their operations and recycled products can be rendered safe.

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1 INTRODUCTION

1.1 BACKGROUND

The amount of plastic waste generated in India is growing rapidly and currently reaches around 5.6 million tons per year (Mahapatra, 2013). In addition, India imports increasing amounts of plastic scrap from developed countries, which are looking for inexpensive solutions to dispose their waste plastic. Plastic recycling rates in India are estimated at 50-60% (Mutha et al., 2006), much higher than plastic recycling rates of <30% in Europe (PlasticsEurope, 2014) and <10% in the United States (US EPA, 2014). Most of the plastic recycling in India takes place in the so-called informal sector, providing livelihood to many, but being done with little regard for worker safety and environmental protection, and without control or monitoring by the government.

Plastic recycling is by and large a sustainable activity: It avoids production of virgin plastics from fossil fuel, carbon dioxide emissions and landfilling. However, certain fractions of plastic waste such as those found in waste electrical and electronic equipment (WEEE) may contain hazardous substances and require specific treatment and, in some cases, destruction. Hazardous plastic additives include brominated flame retardants (used for fireproofing) and heavy metals such as lead (stabilizer and pigment), cadmium (pigment) and antimony (catalyst for flame retardant). Exposure to those substances can have considerable health effects, such as cancer, damage to nervous and reproductive systems, and behavioural changes (Sepúlveda et al., 2010). In European countries, the recycling of plastic is strictly regulated and hazardous plastics are usually diverted from recycling processes and destroyed in controlled incinerators and/or cement kilns. Uncontrolled recycling of such problematic plastics, such as done in the Indian informal sector, entails the risk that toxic substances will be released into the environment. It therefore represents a potential source of harm for humans and other living species.

1.2 SCOPE AND AIM OF THE STUDY

This report presents the results of a study conducted within the Sustainable Recycling Industries programme (SRI), which is funded by the Swiss State Secretariat of Economic Affairs (SECO), and is implemented by the Swiss Federal Laboratories for Materials Science and Technology (Empa), the World Resources Forum (WRF) and ecoinvent. The SRI recycling project in India aims to remove plastics containing hazardous additives from secondary material cycles through an approach which includes applied scientific research, technological partnerships with informal and formal recyclers, market-based mechanisms and the design and implementation of effective rules and standards.

A necessary first step towards the elimination of hazardous plastics from recycling processes is to develop and/or adapt methods that allow recyclers to identify and segregate those plastics from the mainstream. These methods should be simple and robust enough to be implemented in informal settings, where most plastic recycling occurs. Due to their potential POP status (Persistent Organic Pollutants) under the Stockholm Convention, brominated flame retardants (BFRs) were prioritized.

In this context, this study aims at answering the following question: Which hazardous additives limit the recycling of high-quality plastics from e-waste such as housings? How can plastics containing these additives be identified and segregated in informal recycling units such as found in India? To answer these guiding questions, desk research and visits in Swiss WEEE recycling units were undertaken to identify possible technologies to identify and separate BFR plastics. Subsequently, several months were spent in Delhi to understand the informal plastic recycling system and assess the current fate of BFR plastics. Additionally, a sampling and testing campaign was undertaken to assess the efficiency of BFR plastic separation methods considered as applicable in the informal sector.

1.3 OUTLINE OF THE REPORT

This report is divided into six chapters:

- Chapter 1 introduces the background of the study, and sets up its scope and aim.
- Chapter 2 describes the challenges of recycling WEEE plastics, with a focus on the management of BFR plastics from housings. According to internationally defined best practices, BFR plastics should be separated and diverted from recycling processes. In this chapter, an overview of separation methods that can be used for that purpose is offered.
- Chapter 3 presents the findings of several months of desk and field research spent to provide a deeper understanding of Delhi's informal plastic recycling system, taken as a proxy for the Indian situation. It invites the reader to take a tour along the informal plastic recycling chain, and investigates the fate of BFR plastics in this cycle.
- Chapter 4 contains the design and results of a sampling and material testing study undertaken in order to generate much needed data on the BFR content of some streams of plastic found in the informal sector, as well as on the removal efficiency of some simple techniques such as the sink/float method.
- Chapter 5 concludes this report, summarizing the main findings and their implications as well as drawing up some recommendations for further research.

2 RECYCLING OF WEEE PLASTICS – NEED FOR BFR SEPARATION

2.1 INTRODUCTION

Waste electrical and electronic equipment (WEEE) has become an issue of prime interest over the past decades, due to the numerous economic, social and environmental challenges faced globally by those involved with the management of this fast-growing waste stream (Schluep et al., 2009). In many countries, large efforts were deployed to foster the sound recycling of recoverable WEEE fractions (e.g. precious metals, copper, high-value polymers), and the safe management of hazardous components (e.g. batteries, fluorescent tubes, cathode ray tubes, brominated plastics). A large chunk of WEEE consists of plastics, and especially of so-called engineering plastics, being of higher price and having better mechanical and/or thermal properties than the “common” plastics used e.g. for bottles and packaging. As a result, many WEEE plastics are considered attractive for recycling. However, technical challenges have so far hampered high recovery rates in most countries (Buekens and Yang, 2014). The presence of hazardous additives that need to be separated is one of those challenges.

On average, about 20% of WEEE by weight is plastic, with large variations between different products or categories of products (Wäger et al., 2010a). While electrical tools, lightning equipment and medical devices usually contain less than 10% of plastic, shares of above 50% are common in ICT equipment (e.g. computers, printers, telephones) and small household appliances (e.g. vacuum cleaners, toasters, clocks). Up to 300 different types of plastics can be found in WEEE, but three types are dominant, contributing to about three quarters of all WEEE plastics (Dimitrakakis et al., 2009; Maris et al., 2015; Peeters et al., 2014; Schlummer et al., 2007; Wäger et al., 2010a): Acrylonitrile butadiene styrene (ABS, 30-35%), high impact polystyrene (HIPS, 20-25%) and polypropylene (PP, 20-30%).

Due to the presence of electric currents in EEE, the inherent flammability of most plastics, and the widespread use of EEE in houses and offices, flame-retarding compounds are commonly used in those plastic parts of EEE that are especially subject to ignition. These include cables, switches, printed circuit boards and outer casings (exposed to external sources of fire, e.g. candles). As a result, 20 to 25% of all plastics contained in EEE contains flame retardants (FRs) (Morf et al., 2005; Tange and Slijkhuis, 2009). Large variations in FR occurrence exist between different EEE categories, ranging from below 5% in large household appliances (e.g. fridges, washing machines, dishwashers, etc.) to about 80% in electrical tools (e.g. drills, saws, electric lawnmowers, etc.) (Wäger et al., 2010a). More than 175 different types of FRs are available, belonging to one of the following categories; halogenated organic compounds (bromine- or chlorine- based), phosphorus-containing compounds, nitrogen-containing compounds, and inorganic flame-retardants (e.g. aluminium- or magnesium- based). The type of FR compound used depends on the on the polymer type. For instance, HIPS and ABS used in EEE are most often flame-retarded using brominated flame retardants (BFRs), whereas Polycarbonate/ABS blends (PC/ABS) are usually flame-retarded using phosphorus-based FRs (PFRs). Some resins, such as PVC, have relatively good intrinsic flame retarding properties and mostly do not require additional FR compounds.

BFRs are one of the largest groups of FRs and accounted for about 20% of the global FR consumption in 2011 (Townsend Solutions, 2012). The main consumer of BFRs is the electronics industry, and it is estimated that 40% of all FR plastic found in WEEE is also BFR (Tange and Slijkhuis, 2009). About 30-40 different BFR compounds are used in EEE (Brusselaers et al., 2006), the most widely used being Tetrabromobisphenol A (TBBPA) and Polybrominated diphenyl ethers (PBDEs), particularly

Decabromodiphenyl ether (decaBDE). Those BFRs are mainly used in plastic housings and casings, switches and connectors, cables and printed circuit boards (PCBs). Typical loadings (concentrations) of Br for flame retardant applications are between 4-10%, depending on polymer type and required fire retardation (Table 1). HIPS and ABS additionally require Antimony (Sb) as a synergist, typically in concentrations 1/3 – 1/2 of Br (Weil and Levchik, 2009)

Table 1: Common Br-loadings for FR-applications, % (Weil and Levchik, 2009)

FR rating	HIPS	ABS	PC[1]
No FR (vHB)	0%	0	0
Low FR (v2)	5-7%	6.8%	0
High FR (v0)	10%	9.6%	3.5-5.5%

Over the last decades, concerns have been raised over the toxicity of some BFR compounds. BFRs are widely found in air, sediments and biota, including humans, in a wide range of environments including remote arctic areas (AMAP, 2008), which provides evidence that some BFRs are persistent in the environment, can undergo long-range transport and have the potential to bioaccumulate. Furthermore, some BFRs and their degradation products exhibit toxic properties that are similar to those of highly toxic substances such as Polychlorinated dibenzo-p-dioxins (PCDDs), dibenzofurans (PCDFs) and polychlorinated biphenyls (PCBs) (Hornung et al., 1996).

In response to these concerns, several national and international regulations have targeted the production, use and end-of-life management of BFRs or BFR-containing materials. These include the Stockholm Convention on Persistent Organic Pollutants (POPs) (Stockholm Convention, 2001), which has been ratified by 152 countries and the EU “RoHS” Directive on the Restriction of the use of certain Hazardous Substances in electrical and electronic equipment (European Union, 2011), which has been adapted and implemented in other countries such as Brazil, Canada, China, India, Japan, Malaysia, Taiwan, Thailand and some US states. In India, RoHS is enshrined in the WEEE (Management) Rules, 2011 (MoEF, 2016). The Stockholm convention has been ratified by India in 2006. However, India has opted to not automatically ratify amendments to the list of controlled substances. The amendment on POP-BFRs has not yet been ratified in national legislation and as such the Stockholm convention in India does not cover POP-BFRs at the moment.

POP-BFRs, i.e. restricted by the Stockholm Convention, are:

- Commercial pentabromodiphenyl ether (c-pentaBDE), which is mainly composed of tetraBDE and pentaBDE congeners;
- Commercial octabromodiphenyl ether (c-octaBDE), mainly composed of hexaBDE and heptaBDE;
- Hexabromocyclododecane (HBCD);
- Hexabromobiphenyl (HBB).

RoHS-BFRs, i.e. restricted by RoHS regulations as found in the EU and in India, are:

- Polybrominated biphenyls (PBBs)
- Polybrominated diphenyls (PBDEs), including pentaBDE, octaBDE and decaBDE

According to RoHS, the sum of concentrations of PBBs and PBDEs must each be below 1000ppm in new EEE. Of the two groups, PBBs were used less

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[1] Polycarbonate (PC) is naturally fire resistant to some extent

It should be noted that the listing of decaBDE as POP-BFR is under discussion.

According to the Stockholm Convention, the production of POP-BFRs is prohibited. Furthermore, according to Article 6 of the Convention, wastes containing POPs must be 'managed in a manner protective of human health and the environment', and signatory countries must therefore take appropriate measures to reduce or eliminate releases of persistent organic pollutants (POPs) from stockpiles and wastes.

and can usually only be found in trace amounts.

RoHS also includes lead, cadmium, hexavalent chromium and mercury, with maximum concentration values (MCVs) of 1000ppm for all substances except cadmium (100ppm).

RoHS does not apply to current stockpiles and wastes. However, recycled materials (e.g. plastics) to be used in new EEE must be RoHS-compliant.

2.2 BEST PRACTICES FOR MANAGEMENT OF BFR PLASTICS

The Secretariat for the Stockholm Convention, in collaboration with UNIDO and UNITAR, developed a Guidance Document on Best Available Techniques (BAT) and Best Environmental Practices (BEP) for the recycling and waste disposal of articles containing polybrominated diphenyl ethers listed under the Stockholm Convention (Stockholm Convention, 2015). The guidance covers various aspects, from the identification and inventory of stockpiles to options for final disposal of articles containing POP-BFR.

The Stockholm Convention calls for a separation and elimination of wastes containing POP-BFRs from the recycling stream as soon as possible in order to avoid the reappearance of those substances in new products. It prohibits the intentional dilution of those substances during recycling processes since the total amount of POPs released in the environment would not be changed. In the Guidance Document, it is recognized that the separation of POP-BFR containing materials from those containing other brominated flame retardants not listed under the Convention is currently difficult due to technological limitations – the identification of specific BFR compounds requires analysis by GC-MS, which is too costly and slow to be used in recycling operations. The document thus acknowledges that in practice, a segregation of Br-containing from Br-free material is required.

The systematic separation of bromine-containing plastics is enshrined in the CENELEC standards (CENELEC, 2014), which is addressed at operators of European WEEE recycling plants. CENELEC is based on the previous voluntary standard WEEELabex, and is set to become an official European Standard, most likely binding in the next revision of the European WEEE Directive (Miotti et al., 2015). As far as BFR plastics are concerned, CENELEC specifies that:

> '*For the plastics fractions that can contain Brominated Flame Retardants (i.e. plastics from all categories of WEEE except Large appliances and Cooling and freezing appliances): if the total Bromine level is known or assumed to be above 2000ppm or if the treatment operator makes no declaration regarding the BFR content, the treatment operator has to ensure (downstream monitoring) the removal and disposal of the Brominated Flame Retardants content; if the total Bromine level is below 2000ppm, the treatment operator complies with the depollution requirement for BFR*' (CENELEC, 2014).

Therefore, plastic containing more than 2000ppm bromine (i.e., 0.2%) should be considered as BFR plastic to be treated in a facility able to remove restricted BFRs. Under European conditions, plastic containing less than 2000ppm bromine is usually RoHS compliant (<1000ppm PBDEs) as non-RoHS BFRs are nowadays the major compounds found in the respective waste streams.

According to the CENELEC standard, two levels of separation can be applied by operators depending on the technology available at their disposition:

1. Separation level 1: Removal of plastic fraction containing BFRs;
2. Separation level 2: Removal of plastic fraction containing restricted BFRs.

Due to the technological challenges of attaining the second level of separation, most BFR plastics (defined as containing above 2000ppm bromine) are sent for destruction in Europe, either in controlled waste incinerators or cement kilns, without any further de-pollution.

2.3 BFR PLASTICS IDENTIFICATION & SORTING TECHNOLOGIES

Several methods can be used to identify and separate bromine-rich plastic waste streams during recycling operations. They can be broadly divided into manual and mechanical methods:

- Manual methods require the inspection of each individual plastic, usually before shredding, either fully manually (based on markings or on the source (product) of plastics), or semi-manually (with the help of hand-held instruments);
- Mechanical methods can be run in batch or continuously, usually after shredding.

Based on an extensive literature review, eight methods were considered as potentially effective to separate BFR plastics in this study, listed in Table 2. It should be noted that different methods can be combined to improve separation efficiencies. For instance, a combination of simple methods could include source segregation (i.e. knowledge-based screening of products likely to contain BFR), sink/float separation (allowing batch separation) and Beilstein test screening (as on-spot method to verify removal efficiency of sink/float separation).

Table 2: Identification and separation methods for BFR plastics

	Method	Rationale	Detects	Precision	Price (USD)	Applicable in informal sector	EHS concerns
Manual	Visual (markings)	FR indication on pieces	–	Insufficient	Free	Yes	None
	Source segregation	Some WEEE streams are almost BFR-free	–	Medium	Free	Yes	
	Beilstein test	Heated copper wire form Cu-Halogens which emit a green flame	Halogens (Cl, Br, I, not F)	Unknown	~10	Yes	Forming of potentially hazardous fumes
	Sliding Spark Spectrometer (handheld)	Spark evaporates plastic, elements release specific optical spectra	Br, Cl, other	Sufficient for sorting	~6’000	No	

	X-ray fluorescence (handheld)	Absorbed X-ray are reemitted according to spectral lines	Br, Cl, heavy metals	Very high	~30’000-50’000	No	Improper handling of device
	Laser-induced plasma spectroscopy (handheld)	A laser pulse removes some surface material is analysed using optical or mass spectrometry	Br, Cl	Very high	~35’000	No	
Mechanical	X-ray transmission (online)	Absorbance of X ray spectrum by elements, directed air pressure removes particles	Br, Cl, other	Very high	~500’000	No	None
	Sink-float	Br-containing plastic has a higher density	Br, Cl, other	Depends on feed	10-100’000	Yes	

2.3.1 VISUAL SEPARATION (MARKINGS)

According to the ISO 11469 standard (ISO, 2000a), polymeric components weighing in excess of 100 grams should be marked according to their type and content in fillers, plasticizers and flame retardants in order to facilitate efficient identification, separation and processing for recycling at the end-of-life. The associated ISO 1043 series of standards specify symbols to be used for plastic types (Part 1 (ISO, 2011a)), fillers and reinforcing materials (Part 2 (ISO, 2000b)), plasticizers (Part 3 (ISO, 2011b)) and flame retardant (Part 4 (ISO, 1998)).

Therefore, a marking should be added to each polymer during manufacture, giving information on its content. For instance, a component made of polypropylene (PP), reinforced by the addition of 30% of glass fibre, and to which was added epoxidized lineseed oil (ELO) as plasticizer and red phosphorus as flame retardant, should have the following marking (Figure 1):

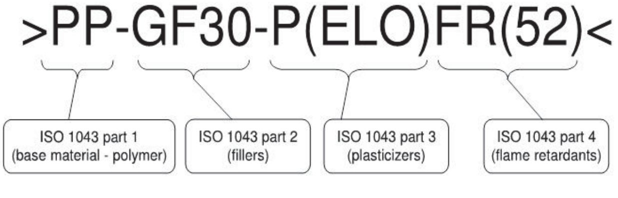

Figure 1: Example of ISO marking system

All plastics containing flame retardants that have been intentionally added or that exceed 1% by weight must include the flame retardant code. The codes for most commonly used flame retardants are listed in Table 2.

Table 3: ISO 1043 codes for commonly used flame retardants (ISO, 1998). Codes which indicate BFRs are listed in bold, codes which may contain POP-BFR not common in WEEE (HBCD) in orange, codes which may contain RoHS / POP-BFRs in red.

Type	Code	Description
Halogenated compounds	**14**	aliphatic/alicyclic brominated compounds
	15	aliphatic/alicyclic brominated compounds in combination with antimony compound
	16	aromatic brominated compounds (excluding brominated diphenyl ether and biphenyls)
	17	aromatic brominated compounds (excluding brominated diphenyl ether and biphenyls) in combination with antimony compounds
	18	polybrominated diphenyl ether
	19	polybrominated diphenyl ether in combination with antimony compounds
	20	polybrominated biphenyls
	21	polybrominated biphenyls in combination with antimony compounds
	22	aliphatic/alicyclic chlorinated and brominated compounds
	25	aliphatic fluorinated compounds
Nitrogen compounds	30	nitrogen compounds (confined to melamine, melamine cyanurate, urea)
Organic phosphorus compounds	40	halogen-free organic phosphorus compounds
	41	chlorinated organic phosphorus compounds
	42	brominated organic phosphorus compounds
Inorganic phosphorus compounds	50	ammonium orthophosphates
	51	ammonium polyphosphates
	52	red phosphorus
Metal oxides, metal hydroxides, metal salts	60	aluminium hydroxide
	61	magnesium hydroxide
	62	antimony(III) oxide

If all plastic parts found in WEEE were marked following strictly the ISO standard, BFR plastics could simply be recognized by reading the markings. However, in practice, many unmarked or mismarked plastics arrive in WEEE recycling facilities. In addition, ISO 11469's detailed marking scheme has only been in use for a few years, while the problematic BFRs had been used already before. Furthermore, finding and deciphering markings is relatively time-consuming, and a systematic inspection would considerably slow down recycling processes. For these reasons, relying on plastic markings cannot be the only method to identify and separate BFR plastics, but it could provide a simple and inexpensive crosschecking method.

Being free of investment costs, relatively simple, and labour-intensive, this method is well suited for the conditions found in the informal sector. A limitation is however the need for basic literacy, which often lacks among informal plastic waste sorters.

2.3.2 SOURCE SEGREGATION

Historically, most BFRs were added to a few types of products such as brown goods and IT equipment, and within those to a few parts, such as housings and casings, switches and connectors, cables and printed circuit boards (PCBs). Furthermore, BFRs are mostly often added to a few plastic types such as ABS and HIPS. Historical applications for restricted BFRs, such as PBDEs, are even more restricted. On the other hand, large categories of products, such as white goods, can be expected to be mostly BFR-free. This heterogeneity in BFR applications can be harnessed to screen products according to their likelihood of containing restricted BFRs or BFRs in general. Sampling and testing studies provide the necessary knowledge basis for such a screening.

Arguably, one the most extensive of such studies has been conducted by (Wäger et al., 2010a, 2010b), which included 53 sampling campaigns for mixed plastics from WEEE undertaken among 15 European WEEE recycling units. Samples were analysed with regard to RoHS-regulated flame retardants (PBBs, PBDEs) and heavy metals (cadmium, chromium, mercury, and lead). Results show that the most BFR-rich plastics fractions are found in small household appliances for high temperature applications, in CRT monitors and in consumer equipment, in particular CRT TVs. The outcomes of their study are summarized in Table 4.

Table 4: Simplified classification of concentrations of RoHS-BFRs found in European mixed WEEE plastics (Wäger et al., 2010a). In green: average concentration more than one order of magnitude below 1000ppm; in orange: average concentration below but close to 1000ppm; in red: average concentration above 1000ppm.

WEEE category	Description	ABS	HIPS	PP
1. Large household appliances	Mixed	🟧	🟧	🟧
2. Small household appliances	Mixed	🟩	🟩	🟩
	Vacuum cleaners, high temperature applications	🟧	🟧	🟩
3. ICT equipment	Mixed w/o screens	🟧	🟧	🟩
	CRTs	🟥	🟥	🟩
	Flat screens	🟩	🟩	🟩
	Printers	🟧	🟧	🟩
4. Consumer equipment	Mixed w/o screens	🟧	🟧	🟩
	CRT TVs	🟥	🟥	🟩

Similarly, a report prepared for the New Zealand Ministry for the Environment (ENVIRON Australia, 2013) contains 'Risk Based Decision Tables' to separate plastics from TVs, business machines (photocopiers/printers/scanners/faxes), computers and peripherals, and white goods. These tables were derived from measurements of BFR levels (down to individual BFR congeners) in a large number of plastic samples, and indicate whether plastic components are likely to contain restricted BFRs, based on their type (e.g. CRT or LCD TV) and year of manufacture.

The systematic separation of plastics from CRT casings in many European WEEE recycling units provides an example of such source segregation. Such knowledge-based screening is necessary to separate BFR plastics in an efficient manner, and it is justified by the fact that most WEEE plastics are BFR-free. However, due to the complexity of WEEE plastic streams, source segregation cannot be rendered reliable enough to guarantee by itself an efficient separation of BFR plastics. It should rather be considered as a useful initial screening method that can be used to concentrate plastic fractions most likely to contain high levels of BFRs (e.g. CRT casings).

Source segregation could be implemented in the Indian informal sector, as it fits well the current sorting practices and does not require any additional infrastructure. In fact, some informal plastic recyclers presently pre-sort plastics likely to contain flame retardants (not specifically BFRs) based on their source (i.e. CRT casings are known to be FR-rich).

2.3.3 BEILSTEIN TEST

The Beilstein test is a simple chemical test used in chemistry as a qualitative test for halogens (Beilstein, 1872). The method is simple; a copper wire is cleaned and heated in a Bunsen burner flame to form a coating of copper(II) oxide. It is then dipped in the sample to be tested (which can be plastic) and once again heated in a flame. A positive test is indicated by a green flame caused by the formation of a copper halide.

Figure 2: Beilstein test to detect BFR plastics

The Beilstein test has previously been used to detect BFRs in plastic samples, with a reported detection limit of 1% bromine and no experienced false positives (BUWAL, 2004; Miguel and Laboa, 2001). The method is however not able to distinguish between different halogens, and a positive Beilstein test (i.e., green flame) could therefore equally indicate the presence of chlorine (e.g. in PVC or due to the presence of chlorinated flame retardants), bromine (e.g. due to the presence of BFRs) or other halogens. However, unless PVC is present in the plastic samples to be tested, a positive Beilstein test most likely indicates the presence of BFRs when WEEE plastics are tested.

Scholz-boiltcher et al. (1992) observed that performing the Beilstein test on chlorinated organic materials leads to the formation of highly toxic polychlorinated dibenzo-p-dioxins (PCDD) and furans (PCDF). This can be explained by the fact that copper acts as a catalyst for the formation of PCDD and PCDF during thermal treatment. Their calculations demonstrate that, depending on the chlorinated compound used, a single Beilstein test can easily exceed the daily tolerance levels set by the German Federal Health Agency of that time. A substitution for the Beilstein test for halides is thus recommended. If substitution is not practicable, Beilstein tests should be only carried out under a fume hood equipped with a charcoal filter and a UV lamp for decontamination purposes. In order to reduce the amount of PCDD/Fs formed during the Beilstein test, Fontana and Goldfarb (1997) recommend minimizing the copper wire diameter and/or diluting samples in solvents such as methanol or acetone. The literature on toxicity of Beilstein test focuses on PCDD/F generated when liquid chlorinated substances are tested. No information exists on the toxicity of using the Beilstein test to detect BFRs in plastics. It is not sure whether polybrominated dibenzo-p-dioxins (PBDD) and -furans (PBDF) can be produced, and the toxicity of those substances is also poorly characterized (van den Berg et al., 2013).

Tests conducted at Empa suggest that the Beilstein test can reliably detect BFRs in plastics (samples prepared with HDPE and decaBDE) to concentrations as low as 0.5% Br (5000ppm) in dark environments. Using copper wires of different diameters, we were able to conclude that a detection limit of 0.5% is guaranteed with a copper as thin as 0.3mm (diameter). Using such a thin wire considerably reduces the amount of dioxins/furans produced (Fontana and Goldfarb, 1997), and also makes it possible to use a simple butane lighter to perform the test.

In sum, the Beilstein test could provide a simple (no sample preparation needed), very inexpensive (only copper wire and a butane lighter are needed), rapid (1-2s per sample) and relatively accurate (to detect plastics where BFRs were intentionally added, i.e. with 5-10% BFR) on-site method to identify BFR plastics. However, due to unknown but probably significant health risks, especially if performed repeatedly, the Beilstein test should always be performed using a fume extraction system.

Due to its simplicity, both in terms of knowledge and material needed, the Beilstein test has the potential to become the most cost-effective method to reliably identify BFR plastics in the informal sector. The potential health hazards associated with the method however call for a special attention to safety precautions. A possible solution would be to design a "Beilstein apparatus" including a simple fume extraction system (e.g. PU foam/glass wool and pump).

2.3.4 SLIDING-SPARK SPECTROMETRY (SSS)

SSS is a surface screening method capable of rapidly detecting bromine, chlorine and inorganic additives above approx. 1000ppm. The basic principle of SSS is the thermal vaporisation of a small amount of plastic at the surface using a train of defined high-current sliding sparks. The material components in the spark plasma are vaporized, atomized and activated to emit light. Elements such as chlorine and bromine emit characteristic radiations in the optical spectra, the intensities of which indicate the concentrations of those elements (Iosys, 2011).

Simple handheld SSS instruments are commercially available, at around 6'000 USD, and allow rapid (about 1 second per sample) and on-site analysis of plastic parts with no sample preparation required except the removal of dust, dirt or stickers. For practical reasons, recyclers often set the system to detect bromine above 1% in order to screen out BFR-containing plastics and not remove plastics with trace concentrations (Stockholm Convention, 2015). SSS is one of the most widely used manual technologies to identify BFR plastics, as it is relatively inexpensive in comparison with alternative instrumental techniques and do not require much training to be used.

Figure 3: Handheld sliding spark spectrometer for detection of BFR plastics (Iosys, 2011)

Small amounts of fumes are produced when sparks are supplied, the composition of which is unknown. It is however possible that, when BFR plastics are spark-ignited, those fumes contain toxic substances such as brominated dioxins and furans. Good ventilation of the workplace is generally sufficient to keep worker exposure below EU and Swiss regulations

SSS is well adapted to settings found in WEEE recycling factories of the industrialized world, but is probably too expensive, complicated, fragile, and high-maintenance to be implemented in informal units of the developing world.

2.3.5 X-RAY FLUORESCENCE (XRF)

XRF is a non-destructive analytical technique used to determine the elemental composition of materials, especially the content in heavy elements. XRF analyzers determine the chemistry of a sample by measuring the spectrum of the characteristic X-rays emitted by the different elements in the sample when it is illuminated by high-energy photons (X-rays or gamma rays).

Handheld and benchtop XRF instruments are commercially available for the quantification of heavy atoms commonly present in WEEE plastic samples, such as bromine, lead, cadmium, mercury, and chromium, with a detection limit of 10ppm to 100ppm and a measurement time below one minute per sample. Handheld XRF instruments, more adapted for on-site screening in recycling facilities than benchtop devices, are available at a cost between 30’000 USD and 50’000 USD (Stockholm Convention, 2015). In comparison with SSS, XRF technology is more costly but more precise, allowing detection of plastics where presence of BFRs is unintentional and due to cross-contamination during previous recycling processes (in the range 100-1000ppm). Sample preparation requirements are similar to SSS (removal of dust, dirt or stickers).

Figure 4: Handheld (left) and benchtop (right) XRF analysers (Olympus, 2015; Oxford Instruments, 2015a)

X-rays are highly hazardous for human health and improper handling of XRF devices could be very detrimental. Potential users thus need to be trained to minimize risks of exposure, and XRF analysis should only be performed in safe conditions.

Due to potential health hazards, high costs and maintenance needs and complexity, XRF analysers are not suited to be used in small-scale, low-capital, informal plastic recycling businesses such as found in India.

2.3.6 LASER-BASED METHODS (LIBS/LIPS/LIMES)

Laser Induced Breakdown Spectroscopy (LIBS) (also known as Laser Induced Plasma Spectroscopy (LIPS) and Laser Induced Multi Emission Spectroscopy (LIMES) is a simple, relatively inexpensive analytical technique to determine the elemental composition of solid, liquid or gas samples. A powerful laser beam focussed on the sample surface evaporates a small amount and excites it to the plasma. Spectral lines emitted, in the ultraviolet zone, describe the elemental composition of the sample. The method has been shown to reliably detect bromine in plastic samples above a Br content of 1.5% (Freegard et al., 2006). Handheld instruments are available at approximately 35’000 USD, requiring minimal sample preparation and allowing rapid analysis.

Figure 5: Handheld LIBS (Oxford Instruments, 2015b)

As it does not use ionizing radiation, LIBS can be considered as safer than XRF. It however produces powerful laser beams that can be dangerous to human sight. Therefore, users of LIBS devices should be trained to minimize exposure.

When it comes to being used in informal settings, LIBS suffers from the same weaknesses as SSS and XRF; expensive, complicated, fragile, high-maintenance, and potential health hazards.

2.3.7 X-RAY TRANSMISSION (XRT)

XRT technology uses high-resolution X-ray transmission image processing to separate materials and waste streams based on specific atomic density. In contrast to handheld screening instruments such as SSS, XRF and LIBS, XRT is used to sort scrap automatically. Online XRT sorting machines are available at approximately 400’000 USD, and are able to sort up to 1 ton of scrap per hour. The technology is used in European and Swiss recycling units (Stockholm Convention, 2015).

Figure 6: Automated XRT sorting machine (Titech, 2015)

Besides its potential use to separate BFR plastics, XRT sorting machines can be used to separate and isolate different WEEE fractions from a mixed input (e.g. ferrous metals, CRT glass, aluminium, etc.). Its high cost however prohibits its use in small-scale recycling operations, even those in industrialized nations.

2.3.8 SINK/FLOAT

Different plastic types often have different densities, and the presence of additives such as BFRs in plastics also exerts an influence on their density. The density ranges of plastics most commonly found in WEEE are displayed in Figure 7. As a reminder, ABS, HIPS and PP make up about 80% of all plastics used in EEE, and BFR plastics are almost exclusively ABS and HIPS.

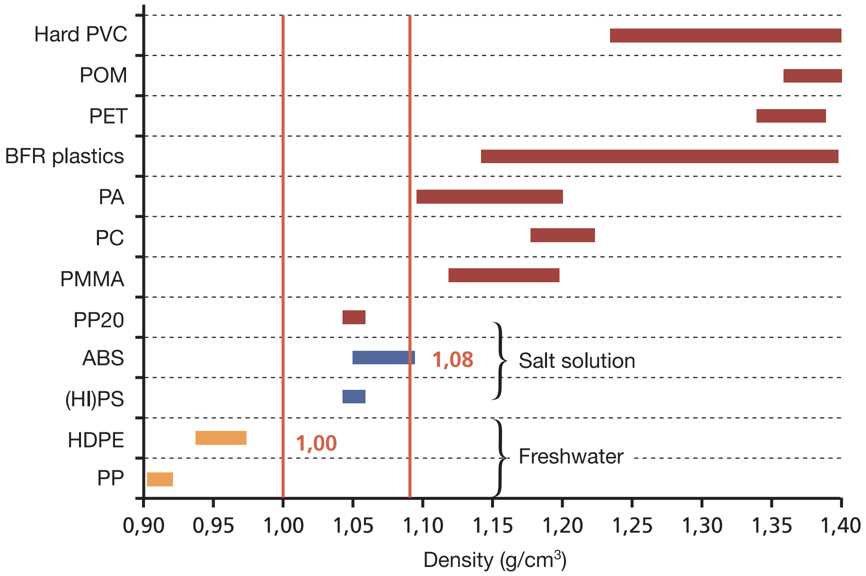

Figure 7: Density range of WEEE plastics and possible separation levels (adapted from Köhnlechner, 2012)

Using solutions of various densities, it becomes possible to separate relatively heavy and light fractions using the so-called sink/float, or density separation, method. Simple solutions can be used; such as freshwater to separate polyolefins (PE, PP) from other plastics, water/ethanol mixtures to separate plastics with densities lower than freshwater (e.g. PE from PP), or salt solutions (e.g. with NaCl) to separate polymers with higher densities (e.g. ABS/HIPS/PP20 from heavier plastics). Sink/float baths of different densities can be arranged in series to obtain several homogenous fractions.

The sink/float technique has been used to separate BFR plastics, which are significantly denser than their non-FR fractions counterpart (Schlummer and Mäurer, 2006). When a solution with a density of around 1.08-1.10 g/cm^3 is used, the floating fraction can be expected to be free of plastics where BFRs where intentionally added (as opposed to those where BFRs occur as trace contaminants due to previous recycling processes), while the sinking fraction will contain BFR plastics present in the input feed, and potentially other polymer fractions of higher density (e.g. PC, PVC, PET). Due to overlaps in the density ranges of several plastic types, additional sorting steps are required before or after sink/float to obtain homogenous fractions in terms of plastic types.

Using manually sorted ABS plastics from CRT casings, collected in an informal plastic recycling unit of Delhi, the density distribution of ABS plastics and the effectiveness of the sink/float method compared to the Beilstein method was investigated. About 200 plastic flakes (of size between 10-50mm) were immersed into a freshwater bath, to which NaCl was gradually added. After each addition of salt, the solution was stirred and floating flakes were removed, counted and tested using the Beilstein test. Theoretical relations between NaCl content and density, as well as results of Beilstein screening are displayed in Figure 8. Flakes floating in a solution with less than 120 g NaCl per litre of water (i.e., density of about 1.08 g/cm^3) were all Beilstein-negative (i.e., no green flame), while remaining sinking flakes were all Beilstein-positive (i.e., green flame indicating the presence of halogens, in this case most likely bromine). In this trial, the density of Beilstein-positive flakes ranged between 1.15 and 1.20 g/cm^3.

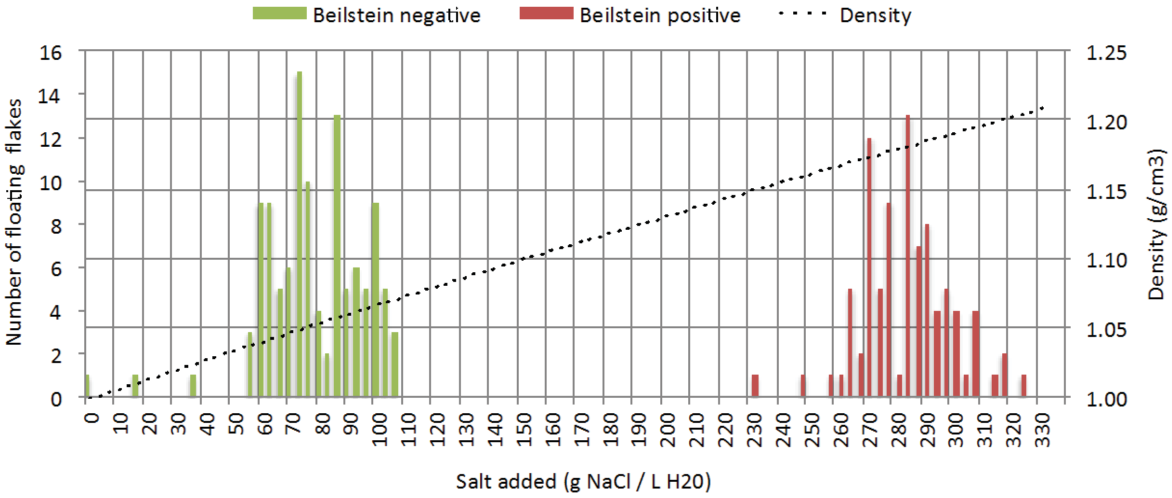

Figure 8: Sink/float separation and Beilstein screening trials with ABS flakes obtained from the informal recycling sector in Delhi (density curve for water at 25°C)

The sink/float method is already used in the Indian informal plastic recycling sector, to separate various plastic fractions (see p.26). As of now, it is not used to separate BFR plastics specifically, as there is no awareness of the existence of this particular fraction; any flame-retarded plastic is considered as “FR plastic”, which is sometimes separated using the sink/float method. Refining existing sink/float separation techniques is therefore potentially the simplest and most cost-effective way to implement BFR separation in the informal sector.

3 FIELD RESEARCH – ALONG DELHI'S INFORMAL RECYCLING CHAIN

3.1 INTRODUCTION

Plastic recycling is a major economic activity in Delhi, involving tens, if not hundreds, of thousands people whose main activity is to create value out of plastic waste generated, both within the city borders and in other parts of India and of the World[2]. The large majority of plastic recycling units belong to the informal sector, characterized by low levels of organization, minimum fixed capital (e.g. machinery), and non-compliance to rules and regulations related to tax, minimum wages, workers safety and environmental protection. Due to the informal nature of most plastic recycling units in the city, it is almost impossible to obtain accurate data on the number of people and volumes of plastic flowing through these recovery channels. Tentative estimates range between 7'000 and more than 50'000 units, employing from 20'000 up to more than 100'000 workers (Gill, 2010; Toxics Link, 2012). The wide variations between these numbers reflect the extreme lack of data on this economic sector.

The recycling system consists of several stages through which plastic waste is collected, sorted, processed, and either recycled into new products, incinerated, or dumped. Plastic waste trade and processing units are scattered across Delhi, with some areas specialized in specific stages of the recycling chain (e.g. dismantling, sorting, pellet making). Besides this clustering effect, most units are also specialized in a few numbers of plastic types. A third type of specialization can be observed in the numerical dominance of the Khatiks, a "Scheduled Caste" (official designations given to various groups of historically disadvantaged and oppressed people in India, also referred to as *Dalits* or, earlier, as "untouchables"). Khatiks were traditionally associated with "unclean" activities such as pig-breeding, pork butchery and bristle trade (i.e., stiff hair of animal, such as pig, used to make brushes). They have since diversified into the recycling of modern materials such as plastic wastes. Up to 90% of workers in the plastic recycling system belong to the Khatik caste (Gill, 2010). Usual exceptions are workers operating shredding and pelletizing machines, particularly unsafe activities which are often conducted by migrants from the poor neighbouring state of Bihar belonging to other castes.

3.2 THE INFORMAL PLASTIC CYCLE

This section provides a better understanding of the plastic recycling system found in Delhi, with a focus on units dealing with WEEE housings (i.e., mostly ABS and/or HIPS). Although many of the observations are representative of the informal plastic system as a whole, others are specific to the WEEE plastic subsystem.

The information mostly stems from field visits and interviews conducted between July and October 2015 complementing the information collected by the NGO Toxics Link (Toxics Link, 2016, 2012, 2011) and Kaveri Gill's seminal field research on the demographics, economics and politics defining Delhi's informal plastic recycling sector (Gill, 2010).

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[2] According the UN Comtrade database (UN Comtrade, 2014), more than 250'000 tons of plastic scrap were exported to India in 2014, mainly from the USA (30%), Germany (17%), the UK (10%), Belgium (10%), and the Netherlands (9%). And these are only the official, registered exports. Actual numbers might be much higher. Furthermore, a large amount of plastic-rich waste products, such as WEEE, is legally and illegally exported to India as well, adding up to the volumes treated by informal Indian recyclers.

The data and information presented can be considered of acceptable confidence. Information gathered during field visits may be incomplete and/or inaccurate due to several reasons. Information may have been lost and/or changed during the often needed translation. Some recyclers may have given incorrect information intentionally or due to their own lack of knowledge. Information was collected from a limited number of recyclers and extrapolations were often necessary to characterize the whole informal WEEE plastic recycling sector. Despite these limitations, the collected information was generally sufficiently uniform between different actors.

3.2.1 COLLECTION AND DISMANTLING

Plastics are ubiquitous in modern times and can thus enter the recycling chain from an almost infinite number of sources. However, not all plastic waste is suitable nor profitable for recycling. In a city where most of the waste collection is done by private and informal actors, who operate following a purely commercial logic, this mean that an important fraction of plastic waste, such as lightweight and dirty plastics, remains uncollected and constitutes litter.

There are two important categories of actors in the collection of plastic waste. At the lowest strata of the waste recycling hierarchy, waste pickers (*Kachrawalas*) make a living from collecting wastes found on the streets or in landfills and selling them to waste dealers/processors. Slightly better off, itinerant waste buyers (*Kabaddiwalas*) visit households, shops, or offices, buy their recyclables (paper, glass, plastic, WEEE, etc.), and resell them to *Kabaddishops*. Therefore, in India, waste producers can sell their recyclable waste, which strikingly contrasts with the situation in higher-income countries where waste management and recycling has to be paid for by the waste producer or the public authorities.

In many products, including electronics, plastics are used in a complex mix of materials that may also include metals, glass, foam and rubber. For those products, manual dismantling is often a necessary first step in order to isolate plastic scrap fractions after which it needs to be sorted further before processing.

3.2.2 SORTING

There are more than 50 different types (resins) of plastics, the most widely used being polypropylene (PP), polyethylene (PE), polyvinyl chloride (PVC), polyurethane (PUR), polyethylene terephthalate (PET), and polystyrene (PS). As seen in Chapter 2, the main plastics found in WEEE are ABS, HIPS and PP.

In order to produce relatively pure and homogenous recycled plastic, plastic wastes are sorted by type (resin), colour, and grade (which mainly refers to whether the plastic is virgin, recycled once, or recycled several times). Plastic waste sorters use their (bare) hands, eyes, nose and simple techniques to identify plastic types and assess their grade (Table 5). This pool of techniques, mostly generated within the Khatik community through decades of learning-by-doing, is continuously transmitted and adapted to new polymeric materials with each generation. One plastic scrap dealer, quoted in (Gill, 2010), proudly characterized this indigenous knowledge:

> *'Khatik knowledge of plastics and recycling is unsurpassed – by smelling it, seeing it, and burning it, we can tell what sort of plastic it is. Others have to check with painstaking methods. Because we have imbibed knowledge from childhood, we can tell just from experience what sort of plastic we are dealing with, what processes may be used to recycle it. We know 180-200 items by sight. Our biraderi* (brotherhood) *has maximum knowledge of this work'*

Figure 9: Burn test, to assess flame retardancy (left), and solvent test, to identify plastic type (right)

Such simple, manual, techniques are not only used in Indian informal settings, but also in leading plastic technology institutions such as the KATZ plastic training and technology centre in Switzerland. An example of polymer identification tree provided by KATZ is given in Annex A.

The effective sorting of plastics into different types is one of the most, if not the most, important process in plastic recycling. It is also one of the greatest challenges that face the global plastic recycling industry, largely accounting for the low recycling rates in industrialized nations. Generally speaking, each plastic type should be processed separately in order to produce recycled plastics with good properties. In some cases, even a contamination of 1% suffices to significantly lower the product quality. Other resin mixes are more permissive, allowing a contamination of up to 5% before quality losses. In rare cases two plastic types are fully compatible, meaning that they can be processed together to produce a plastic of good quality (sometimes higher than the original single types). Figure 10 presents a general polymer compatibility matrix, compiled from various sources.

Sorting is performed repeatedly along the recycling chain by most actors. For Dismantlers, *Kabaddiwalas*, *Kabaddishops*, scraps dealers and independent sorters, finer sorting directly translates to increased income. For instance, whereas mixed scrap mostly composed of ABS and HIPS (typically from WEEE) can be sold at 25-30 INR (0.38-0.45 USD[3]) per kg, finely sorted ABS scrap at around 40 INR (0.60 USD) per kg (33-60% value added by sorting), and HIPS scrap at about 35 INR (0.53 USD) per kg (14-40% value added by sorting). Grinders and Recyclers perform last cleaning / spot checks steps to ensure that contaminating polymers are below the compatibility thresholds.

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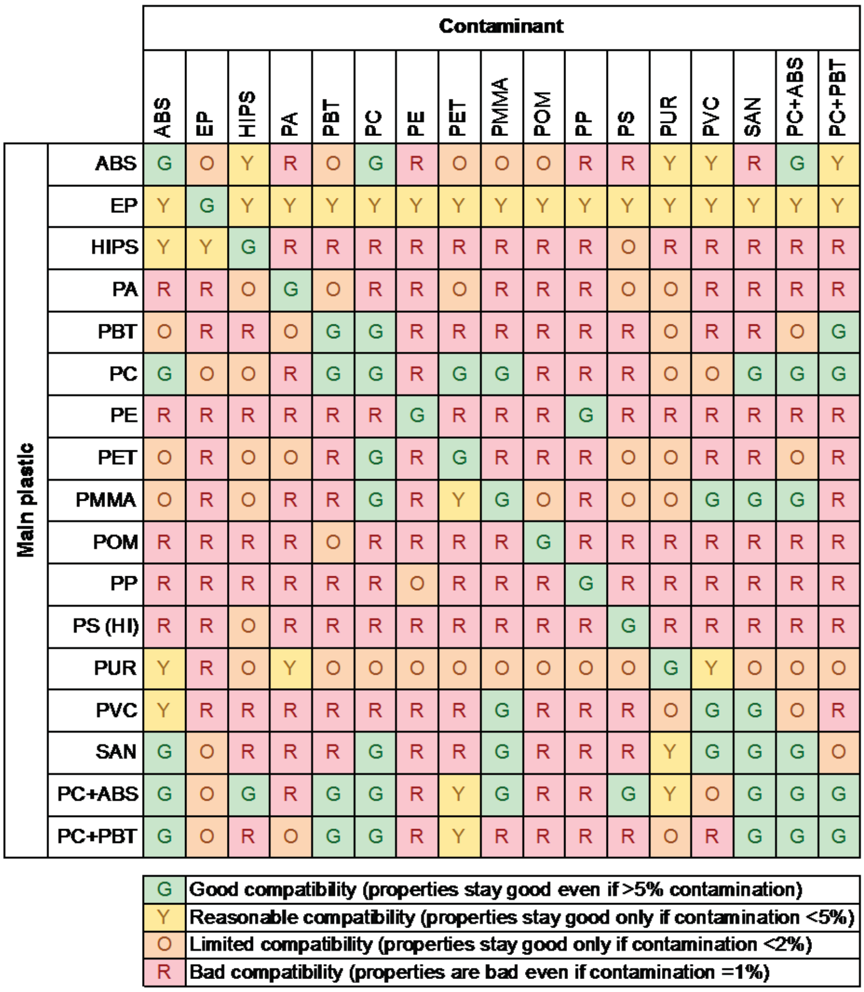
[3] An exchange rate of 1 Indian Rupee (INR) for 0.015 US Dollar (USD) is considered in this report

Table 5: Plastic sorting methods used in the informal sector (focus on WEEE plastics such as ABS, HIPS, PC, PP)

	Separation method	Variables	Used to separate	Remarks/examples
Visual	Source	Product type	Plastic types	*Bisleri* (bottled water brand) refers to PET; *Bata* (shoes manufacturer) refers to PVC; *Doodh theli* ("milk pouch" in Hindi) refers to LDPE
	Colour	Colour	Grey/black/white/crystal/other	Coloured plastics are often not segregated in the case of WEEE plastics
	Appearance	Shininess Visible homogeneity	High- and low-grade (i.e., virgin and recycled)	Virgin plastics are usually shinier, more homogenous
Physical	Tensile/break test	Rigidness Easy to break Break mark	Plastic types	PP is more tensile/less rigid than ABS, which is itself more tensile/less rigid that HIPS (which breaks easily when bent)
	Scratch test	Absence/presence of scratch mark	Plastic types	Fingernail scratch visible on PE, and not on PP
	Touch test	Roughness Brittleness Hardness	High- and low-grade (i.e., virgin and recycled)	Virgin plastics are usually softer, brittler, harder (sometimes assessed by biting)
	Sound test	Sound when hit	Plastic types	Different plastics emit varying sounds when hit
	Sink/Float	Sinks/floats in freshwater Sinks/floats in saltwater (with approximate salt content) Sinks/floats in other solution (e.g. saltwater with caustic soda)	Plastic types	See p.18 for density of plastic types
			Virgin/recycled plastics	Recycled PP (i.e. "low-grade") sinks whereas virgin PP floats (may be due to fillers)
			Non-polymeric materials	Foam, paper, wood, metal, rocks, rubber, dust, etc.
			Flame retarded plastic	No distinction between halogenated, phosphate-based or mineral FRs
Chemical	Solvent test	Sticks Doesn't stick Surface is abraded	Plastic types	So-called "ABS chemical" is used to separate ABS and HIPS, depending on whether the plastic sticks to the finger or not after contact with the chemical (ABS sticks). Exact composition of chemical is unknown, but most likely acetone or acetone-based Some sorters reported using petrol to identify HIPS
	Burn test	Burns Doesn't burn	Flame retarded (FR)/non flame retarded plastics	Most commonly used method to separate flame retarded plastics
	Burn & sniff test	Smoke odour	Plastic types	Different plastics have different smells when burnt, recognizable by skilled workers



		Contaminant																
		ABS	EP	HIPS	PA	PBT	PC	PE	PET	PMMA	POM	PP	PS	PUR	PVC	SAN	PC+ABS	PC+PBT
Main plastic	ABS	G	O	Y	R	O	G	R	O	O	O	R	R	Y	Y	R	G	Y
	EP	Y	G	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	HIPS	Y	Y	G	R	R	R	R	R	R	R	R	O	R	R	R	R	R
	PA	R	R	O	G	O	R	R	O	R	R	R	O	O	R	R	R	R
	PBT	O	R	R	O	G	G	R	R	R	R	R	R	O	R	R	O	G
	PC	G	O	O	R	G	G	R	G	G	R	R	R	O	O	G	G	G
	PE	R	R	R	R	R	R	G	R	R	R	G	R	R	R	R	R	R
	PET	O	R	O	O	R	G	R	G	R	R	R	O	O	R	R	O	R
	PMMA	O	R	O	R	R	G	R	Y	G	O	R	O	O	G	G	G	R
	POM	R	R	R	R	O	R	R	R	R	G	R	R	R	R	R	R	R
	PP	R	R	R	R	R	R	O	R	R	R	G	R	R	R	R	R	R
	PS (HI)	R	R	O	R	R	R	R	R	R	R	R	G	R	R	R	R	R
	PUR	Y	R	O	Y	O	O	O	O	O	O	O	O	G	Y	O	O	O
	PVC	Y	R	R	R	R	R	R	R	G	R	R	R	O	G	G	O	R
	SAN	G	O	R	R	R	G	R	R	G	R	R	R	Y	G	G	G	O
	PC+ABS	G	O	G	R	G	G	R	Y	G	R	R	G	Y	O	G	G	G
	PC+PBT	G	O	R	O	G	G	R	Y	R	R	R	R	O	R	G	G	G

G	Good compatibility (properties stay good even if >5% contamination)
Y	Reasonable compatibility (properties stay good only if contamination <5%)
O	Limited compatibility (properties stay good only if contamination <2%)
R	Bad compatibility (properties are bad even if contamination =1%)

Figure 10: Compatibility of polymers (Bicerano, 2006; Hepp, 2013; Peeters et al., 2014)

It can be considered that, through the variety of visual, physical and chemical sorting methods used by Delhi's experienced plastic waste sorters, most plastic types are segregated in a quite efficient manner. However, the lack of scientific studies on the topic prevents any qualified assessment. Such information would be very valuable to compare this "informal efficiency" with that of sophisticated sorting technologies used in highly developed countries (e.g. infrared, X-ray, or laser spectroscopy, electrostatic separation).

The sorting of plastics by colour is less challenging but nonetheless important. Transparent and white plastics are the most valuable. They can be used to produce pellets of any colour with the addition of pigments and are considered the "purest". Grey plastics (ranging from light to dark grey) are also processed separately either to be mixed with pigments, or to produce grey pellets which find a wide range of applications. Separate channels exist for black plastics as well, processed individually or mixed with coloured plastics and black pigments (e.g. carbon black) before extrusion. In WEEE plastics, coloured plastics (i.e., other than white, grey or black) are usually not segregated due to their relatively low occurrence. For other plastic streams, separate channels for some colours may however exist, although field visits provided no clear evidence of this happening on a large scale.

To informal plastic recyclers, "grade" mostly refers to whether the plastic scrap is virgin, recycled once, ore recycled more than once. Between these categories, prices differences of about 5 INR / kg (0.08

USD / kg) exist on the scrap market. This information is kept along the chain down to the pellet market, where different grades of recycled plastics can be found. Based on the interviews, it can be inferred that after three to four cycles, plastics do not get mechanically recycled anymore due to their poor quality.

Reportedly, one of the only markets for this low-grade plastic scrap is as alternative fuel for brick manufacture. India is the world's second largest producer of bricks, mostly coming from small-scale, informal businesses that use simple and polluting brick-kilns (CSE, 2015; Greentech Knowledge Solutions, 2014). The process requires temperatures of 900-1000°C, which are usually supplied with coal. Some recyclers indicated selling their low-grade, unrecyclable, plastic scrap at 5 INR (0.08 USD) per kg. The price of low-quality coal in India is 3-4 INR/kg. This comparatively higher price is well justified by the higher calorific value of plastics (15 – 40 MJ/kg (Boerrigter, 2000), compared to Indian low-quality coal (12 MJ/kg (Indian Ministry of Coal 2014)).

Dedicated sorting activities often take place in open plots within or around scrap markets, where sorted plastic scrap is sold. Situated on the western outskirts of Delhi, Tikri Kalan is the city's main plastic scrap market, spanning an area of about 50 hectares (Figure 11). The local "PVC and Plastic Waste Dealers Association", formed in response to accusations of environmental pollution brought in front of the National Green Tribunal, regroups some 600 scrap dealers and claims to represent more than 50,000 people engaged in the segregation of plastic waste in the area (delhi.gov.in, 2015; NGT, 2013).

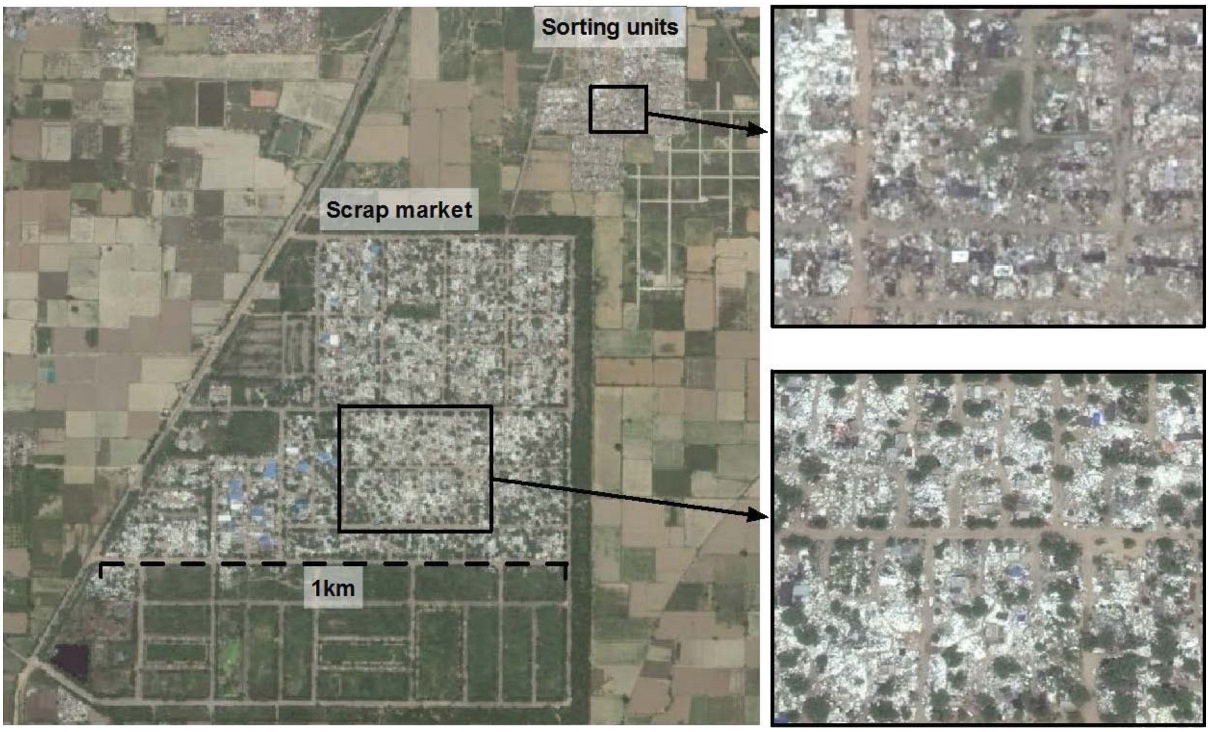


Figure 11: Plastic scrap market and sorting units at Tikri Kalan, New Delhi. Each white spot is a bag containing 100-150kg of plastic scrap. The scrap market spreads out on about 50 hectares (Google Earth, 2015).

3.2.3 SHREDDING

After sorting by type, colour and grade, plastic scrap is sold to shredding units who generally operate a finer segregation. Through this fine sorting, non-polymeric impurities that are bound to the plastic (e.g. screws, plastic-metal parts) can for instance be segregated. In the case that the shredding/pelletizing unit bought relatively homogenous mixed scrap (i.e., mostly 2-3 different resins), this sorting step leads to the segregation of different types according to a set of manual methods. For instance workers usually rely on aspect, tensile/break test, sound test and reaction to "ABS chemical" to segregate an ABS-, HIPS- and PP- rich mixed scrap typical of WEEE.

Finely sorted plastic scrap, at this point still very heterogeneous in size, subsequently enters the shredding process, in which mechanical shredders are used to produce plastic flakes of size between 10 and 50 mm (Figure 12). This is the first process in the informal recycling chain for which machinery is used, as all upstream processes (except transport) are manual.

Figure 12: From left to right: Sorted plastic scrap (ABS from CRT monitors); shredder; plastic flakes

After shredding, some specialized recycling units use the sink/float method to further segregate different fractions. Flakes are immersed in plastic tanks or concrete pools containing a solution, generally made of water and table salt (NaCl). Other solutes with higher solubility in water, such as caustic soda (NaOH), are sometimes used to increase the density of the solution above the salt saturation point (i.e., 359 g NaCl/L water, density ≈1.30 kg/L at 25°C).

Depending on the source of the feed, the sink/float separation can have different objectives:

- When the feed is relatively clean and homogenous, and likely to contain a significant share of flame-retarded plastic (e.g. CRT TVs & monitors), some units use density separation with salt water to obtain a so-called "plain" fraction (floating) and a "FR" fraction (sinking). Workers do not follow specific recipes but add salt or water depending on the floating behaviour on the batch. Sometimes the removal efficiency is verified with a burn test. Prices for FR plastic pellets can be of up to 25% higher than those of the non FR-sorted plastic (Figure 13). The floating fraction can also be sold at higher prices as it contains fewer impurities. Most recyclers agree that the demand for recycled FR plastic is currently too low to justify systematic segregation. Reportedly, demand for FR plastic only arises a couple of times per month, directly from manufacturers of fire-sensitive applications (e.g. electric sockets and switches, electric water pumps, etc.), and is limited to a few plastic types (e.g. ABS but not HIPS).

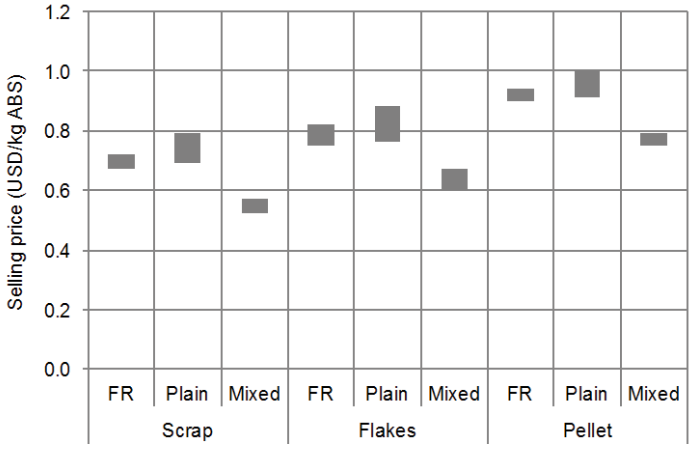


Figure 13: Price ranges for ABS in the informal sector (as of July 2015)

- The sink/float method is also sometimes used to clean “dirty”, heterogeneous, plastic scrap by removing impurities and/or non-target polymers. In the case of ABS, such scrap typically comes from various small household articles (e.g. toys, helmets, recorders), and automotive parts (e.g. car bumpers). Some recyclers immerse such feed, after rough shredding, into salt water at or close to the salt saturation point (i.e., at 1.25-1.30 g/cm^3). The floating fraction is considered as “clean” and suitable for recycling, whereas the sinking fraction, containing a complex mix of denser plastics (e.g. ABS containing fillers or flame retardants) as well as rubber and metal, is considered as “waste” and can be sold as alternative fuel for brick kilns.
- Some recyclers reported using other sink/float processes for other purposes, e.g. to separate PP or PE from heavier plastics (freshwater can be used), PET from lighter plastics (theoretically achievable using density at or close to salt saturation point), and glass-fibre reinforced plastics from lighter plastics using a mix of salt water and caustic soda. Almost two decades ago, in Bangalore, Shah and Rajaram (1997) observed that informal recyclers added alcohol to water resulting in a density below 1 g/cm^3, allowing them to separate PP from PE.

Figure 14: Multi-step density separation using the sink/float method

After shredding and eventual density separation, plastic flakes are usually washed. Relatively clean plastic fractions such as WEEE plastics which spent most of their lifetime indoors may be directly injected into the extruder. Washing is done using water, mixed with caustic soda if flakes are particularly dirty and/or to remove stickers.

If flakes underwent density separation and/or washing, a drying step is necessary before further processing. The drying process usually consists of spreading the flakes on a large open space exposed to the sun, such as rooftops.

Figure 15: Drying of plastic flakes (here, ABS from household articles and automotive parts)

3.2.4 EXTRUSION

Extrusion is the process in which plastic scrap in the form of flakes are melted and formed into a continuous profile to produce homogenous plastic pellets, which can be further used to manufacture finished plastic products.

Before extrusion, plastic flakes are fed into a mixer, where they are heated and mixed with various additives used to enhance the properties of the pellets (e.g. plasticizers, impact modifiers, "shinicizers", compatibilizers, etc.), define their colour (pigments) and/or lower the processing costs (e.g. fillers that fill space in polymer matrix). Some of the additives encountered during field visits include engine oil, ethylene vinyl acetate (EVA), paraffin, carbon black and calcium carbonate.

Homogenous, heated and compounded flakes subsequently undergo extrusion. In simple terms, an extruder is a heated cylinder containing a rotating screw that slowly pushes the plastic forward. The internal friction heats the plastic to its melting temperature (commonly 150°C - 250°C). Electric resistor heaters are often attached to extruders to allow some form of temperature regulation. After passing through a die, homogenous plastic strings leave the end of the cylinder, before being cooled down in water and chopped into small pellets.

Figure 16: Mixer (left) and extruder (right)

Theoretically speaking, the shredding, mixing and extrusion processes taking place in the Indian informal sector are close to those implemented in European recycling facilities. However, the crude equipment used in India allows for little quality control. Heterogeneous mixing, insufficient or excessive amounts of additive, and overheating leading to polymer decomposition are some the technical problems encountered by informal plastic recyclers, that can reduce the quality of their products.

Pellets are generally produced on an order basis. Some units even reported purchasing scrap only after receiving orders for pellets and/or finished product. Depending on the specifications of the order in terms of plastic type, grade, colour, flame retardancy, etc., suitable scrap is purchased and/or sorted from existing in-house scrap.

3.2.5 REMANUFACTURE

Recycled plastic pellets are used to manufacture new plastic products, mainly through injection moulding. Some units have the capacity to host both pellet making and moulding processes, while other sell their pellets to independent moulding units or on pellet markets.

Sadar Bazaar, in Old Delhi, is the city's largest wholesale market and, according to some, Asia's biggest (Gulati, 2011). It is also the main market for plastic pellets. Plastic pellet traders are concentrated in one street (Bahadurgarh Road), where about 250 shops sell pellets made of both virgin and recycled plastic. Virgin plastic sold on the market is mostly imported (from China, Taiwan, Thailand, etc.), while recycled plastic comes exclusively from India. Typically, the prices of recycled pellets are 50-60% of that of virgin plastics. Significant price differences exist between both virgin and recycled pellets depending on their grade (generally visually assessed), colour, or flame retardancy. As of July 2015, recycled ABS pellets were sold at about Rs. 70 per kg (1.05 USD), virgin ABS pellets at Rs. 120 per kg (1.80 USD) and virgin ABS pellets with a flame retardancy of V-0 according to the UL 94 standard (Underwriters Laboratories of the USA, 1994) at Rs. 190 (2.85 USD). Flame-retarded recycled pellets are only found in a couple of shops, which tends to confirm that the demand is low and that transactions are usually done directly between pellet producers and plastic product manufacturers.

Recycled plastic pellets are bought by manufacturers of plastic products, active both in the formal and informal sectors. Depending on the requirements of the application, virgin plastic as well as various additives can be mixed with recycled plastic. Due to the inherent challenges of plastic recycling, as well as to the primitive methods used in the informal sector, recycled plastic is of lower quality than virgin plastic. "Downcycling" into lower quality products such as toys, buckets, car parts and pipes rather than high quality applications is thus common. After three or four life cycles, plastics cannot be recycled anymore and are incinerated (possibly with energy recovery, e.g. for brick-making) or dumped.

Figure 17: Injection moulding machine (left) and recycled plastic part used in water pumps (right)

3.3 BFR PLASTICS: CURRENT SITUATION & POTENTIAL FOR SEPARATION

According to estimates by Frost & Sullivan (2013), between 30 and 40% of the 800'000 tons of WEEE generated in India in 2012 ended up in Delhi. Approximately 90% is handled in the informal sector. Furthermore, the annual growth rate in WEEE production levels from 2005 to 2012 is estimated at 27.4%. By conservative extrapolation, it can be inferred that about 500'000 tons of WEEE were processed in Delhi in 2015. Assuming that, on average, WEEE contains 20% of plastics (Wäger et al., 2010a), and that about 12% of WEEE plastics contain BFRs (Tange and Slijkhuis, 2009), the total amount of BFR plastic processed in Delhi in 2015 can be estimated at 12'000 tons. That is, an average of about 33 tons per day, and this does not include the unknown but probably significant quantities of BFR-containing plastic scrap imported and sold on Delhi's scrap markets.

There is no awareness of BFR plastics in the informal plastic recycling sector. Awareness exists about FR plastics among WEEE plastic recyclers, but not on the specific formulations used to achieve flame retardancy. Recyclers are able to identify and segregate FR plastics, but have no incentives to further distinguish between bromine-, phosphorus-, or aluminium-based FR plastics. FR plastics, of which 80% are BFR on average, are separated through burn test or density separation when specific demand for this type of plastic arises. However, this is the exception rather than the rule, and most BFR plastics end up in the main streams. Their presence in recycled plastic pellets has been confirmed by laboratory analyses, at concentrations lower than required to achieve flame retardancy, which suggests unintentional dilution due to cross-contamination (Toxics Link, 2012).

In order to avoid the cross-contamination of secondary plastics with such harmful substances, a take back system should be implemented to sort out BFR plastics from recycling systems and channelize this stream to sound treatment facilities, such as cement kilns or waste-to-energy plants. For such a take back channel to be successfully implemented in the informal sector, at least two conditions should be met:

- Technical feasibility: appropriate methods to sort out BFR plastics from other scrap must be available. These separation techniques should be inexpensive, simple enough to be used by workers lacking formal education and, often, literacy, robust enough to be used in rough conditions (dust, sun, water, heat, power cuts, etc.), and they should not entail health or environmental hazards.
- Economic feasibility: economic incentives must exist for recyclers to abandon the recycling of BFR plastics, which could be achieved by offering market prices for this stream. The cost-effectiveness of different BFR plastic management options, as well as potential financial schemes to subsidize a take back channel, are considered within the SRI programme.

The present report focuses on the first part. Field visits suggest that informal recyclers are able to separate flame-retarded plastics, either via burn test or through density separation. Assuming that most flame retarding systems used in WEEE plastics are bromine-based, it is possible that current separation methods are sufficient to sort out most of the BFR plastic entering informal recovery systems. However, a lack of scientific studies on this topic prevents from drawing any conclusions. In order to fill in this gap of knowledge, a sampling and material study was undertaken, the design, methodology and results of which are presented in the following chapter.

4 SAMPLING AND TESTING STUDY

4.1 OBJECTIVES

As seen in the previous chapter, BFR plastics are rarely separated in the informal recycling sector. It can therefore be assumed that those potentially hazardous substances are diluted in the mainstream and contaminate the bulk secondary plastic market, exposing a wide range of workers and consumers along the chain. Simple methods such as density separation, burn test and Beilstein test could potentially be effective to sort out BFR plastics from the recycling chain in informal settings. In order to assess this potential and to develop fact-based improvement strategies, a sampling and testing study was conducted. Two central questions guided the design of this study:

- What are the concentrations of hazardous substances, including BFRs but also heavy metals, in different plastic streams found in the informal sector?
- How efficient are simple methods such as density separation, burn test and Beilstein test to sort out BFR plastics in informal settings?

4.2 SAMPLING CAMPAIGN

Based on a review of relevant literature (incl. LAGA (2001), BS EN 14899 (2005), Stenvall et al. (2013), WEEELABEX (2014), Maris et al. (2015)), a sampling strategy was designed to fit this study's objectives and the specificities of Delhi's informal sector.

Samples were selected to be representative of typical plastic streams found in informal recycling units specialized in WEEE plastics (mainly ABS, but also HIPS). This includes the following streams:

- Scrap from single product categories, such as CRT casings or printers, often processed separately;
- Mixed scrap from electrical and electronic equipment;
- Mixed scrap from various household articles (e.g. toys, helmets, radios) and automotive parts.

A particular emphasis was put on collecting plastic samples from CRT casings (both from TVs and computer monitors), for two reasons. First, this stream has been identified as having the highest concentrations of (POP-)BFRs among different WEEE plastic streams (Wäger et al., 2010a). According to the Stockholm Convention Guidance Document for the inventory of POP-PBDEs, CRT casings are expected to contain more than 50% of the total POP-PBDEs present in WEEE plastics (Stockholm Convention, 2012). Second, CRT casings are seen as particularly attractive for informal WEEE recyclers, as they represent a relatively large and homogenous stream of high value plastic with low processing costs (easy to dismantle, reduced washing needs, etc.). Therefore, specialized channels can be found for this stream, with a limited number of recyclers acting as concentrator for these wastes of concern. Other plastic streams often encountered in informal WEEE plastic recycling units, such as mixed scrap from EEE and from various household articles and/or automotive parts, were also collected to allow comparisons.

In order to have samples with a relatively uniform grain size, all samples were collected in a shredded form, i.e. with a typical grain size of 10-50mm. The sampling area consists of four informal recycling units, selected on the basis of three criteria: (i) unit is specialized in WEEE plastics, particularly ABS; (ii) shredding process is part of the operations (samples taken from shredded fraction); and (iii) units owner is willing to share information on processes and plastic samples. Table 6 describes the units included in the sampling campaign. Based on information given by unit owners, it can be estimated that those units together process about 5 tons of WEEE plastics per day. Of these units, one reported using density separation to separate FR plastics (although no such separation was visible at both time the unit was visited), two reported using the burn test on-demand (reportedly rare and in low volumes), and one reported not separating FR plastics at all.

Table 6: Recycling units included in sampling campaign

Unit	Location	Processes	Specialty	Approximate production (kg/day)	Separates FR plastics
A	Mundka	Shredding, extrusion, moulding	ABS, HIPS, PC	1400	Yes, using sink/float method (could not be seen in 2 visits)
B	Mundka	Shredding, extrusion	ABS, PC-ABS, PP	1500-2000 (ABS)	No, due to low demand, but aware of sink/float method
C	Karawal Nagar	Shredding, extrusion	ABS, HIPS	1000	3-4 times/month, using burn test (low volumes)
D	Kirti Nagar	Shredding	ABS, HIPS	1000	Rarely, using burn test (used sink/float before but now demand is low)

In each unit, the following sampling protocol was followed:

1. Identification of fraction to be sampled, which can include:
    a. Flakes with grain size of 10-50mm taken from floating or sinking fraction in sink/float tank or pool;
    b. Flakes with grain size of 10-50mm taken from shredder output pile;
    c. Flakes with grain size of 10-50mm from drying pile;
    d. Flakes with grain size of 10-50mm from several bags of similar content, when no processing of relevant stream takes place at the time of sampling.

2. Collection of about 10 single samples (handfuls) from the fraction to be sampled, in different areas and depths of the pool/pile/bag in order to maximize heterogeneity;
3. Mixing of single samples into one mixed sample, with a target weight of approximately 2 kg, representing a volume of approximately 5 L;

4. Documentation of the input feed (type of product, plastic type, volume, etc.), either by direct observation (if processing at the time of sampling) or from information communicated by workers (if processing prior to sampling).

The sampling campaign was recorded in detail and documented via photographs (excerpts in Annex B).

The sampling procedure followed in this study is based on Wäger et al. (2010a, 2010b) for a study on RoHS substances in European WEEE plastics. However, due to the different sampling conditions encountered in European recycling plants and in informal recycling units in Delhi, several adaptations were necessary (Table 7).

Table 7: Comparison of sampling procedure used in this study with that followed by Wäger et al. (2010b)

Parameter	Used in study by Wäger et al. (2010b)	Used in current study	Remarks
Input quantity	3-7 tons, in single batch	0.3-2 tons	Small scale operations limit input size
Sampling location	Preferably from falling stream, e.g. outlet of conveyor belt	From sink/float bath	Sampling from sink/float bath is similar to sampling from falling stream
		From shredder output pile	Approaching functioning shredder is dangerous (flying flakes)
		From drying pile From bag	Relevant fraction not always processed at time of sampling
Number and size of samples	Input quantity to be sampled with 8 single samples, weighting min. 1kg. 4 randomly chosen single samples are mixed	Input quantity sampled with ~10 single samples of ~0.2 kg (handful). All ~10 samples are	Logistic issues associated with transporting several 4kg samples from recycling unit to storage unit

	to a mixed sample of min. 4kg (min. amounts for grain size 20-50mm)	mixed to a mixed sample of ~2kg	
Sampling period and interval	Sampling period is processing time to obtain 3-7 tons of plastics, sampling interval is sampling period divided by amount of single samples	Samples collected at a single time, but from different areas/depths of the input to approximate different times	Limited availability of time in recycling units

In total, 15 mixed samples were collected from the four selected recycling units (Table 8). Input quantities, estimated based on information provided by recyclers, range between 3 and 2000 kg. The weight of mixed samples ranges between 1.6 and 2.5 kg (average: 2.1 kg). Considering an average weight of 0.8g per flake (n=660 flakes from various samples), it can be estimated that each sample contain between 1900 and 3000 flakes (average: 2586 flakes). Each sample is described by information on plastic type (resin), feed type (products), and other relevant information (e.g. whether sample comes from fraction separated using burn test or density separation).

Some samples come from separate fractions that were originally mixed, but later segregated by recyclers:

1. Samples 5 and 6 originate from a fraction which was originally mixed and subsequently separated into FR and non-FR plastics by the recycler using the burn test.
2. Samples 9 and 10 originate from a fraction which was originally mixed and subsequently separated using density separation by the recycler (unknown density) in order to clean "dirty", heterogeneous, plastic scrap;
3. Samples 14 and 15 originate from the same process as samples 9 and 10.

4.3 METHODS AND RESULTS

A number of methods were used to characterize the samples and generate information on simple BFR separation techniques. Those methods can broadly be classified into two categories:

- Simple BFR plastic separation and screening methods: density separation and Beilstein screening;
- Instrumental methods to reveal composition of samples: elemental analysis by Energy Dispersive X-ray Fluorescence (EDXRF), Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP-OES) and Ion Chromatography (IC).

Methods belonging to the first category were performed in non-laboratory conditions, similar to those found in informal recycling units, whereas methods belonging to the second category were performed in an ISO 17025 accredited laboratory (RoHS laboratory, Centre For Materials For Electronics Technology C-MET, Hyderabad, India). Furthermore, simple separation and screening methods were performed in samples in the form of flakes, while samples were reduced to powder form for the instrumental analysis.

Table 8: List of samples

Sample #	Unit	Date of sampling	Approx. input quantity (kg)	Sample weight (kg)	Approx. number of flakes*	Description**
5	A	07.10.2015	3	2.3	2818	"non FR ABS", from mixed e-plastic (separated by burn test)
6	A	07.10.2015	3	2.1	2665	"FR ABS", from mixed e-plastic (separated by burn test)
7	C	08.10.2015	1000	2.4	2974	"ABS", from CRT monitors (mostly back panel)
8	C	08.10.2015	1000	2.2	2798	"ABS", from CRT monitors (mostly front panel)
9	C	08.10.2015	2000	2.1	2681	"clean ABS", from “household articles and automobile parts (floating in salt water)”
10	C	08.10.2015	2000	2.3	2864	"dirty ABS", from “household articles and automobile parts (sinking in salt water)”
11	D	09.10.2015	1000	2.1	2656	"ABS", from mixed e-plastic (mostly casings from IT equipment e.g. CRT monitors & printers)
12	B	14.10.2015	1000	2.1	2675	"ABS", from mixed e-plastic
13	B	14.10.2015	1000	2.2	2749	"ABS", from cable drums (“made of recycled plastic”)
14	C	30.10.2015	2000	1.9	2340	"clean ABS", from “household articles and automobile parts (floating in salt water)”
15	C	30.10.2015	2000	2.1	2596	"dirty ABS", from “household articles and automobile parts (sinking in salt water)”
16	C	30.10.2015	1000	1.7	2145	"HIPS", from CRT TVs
17	C	30.10.2015	1000	1.6	1968	"ABS", from “printers”
18	C	30.10.2015	1000	2.0	2494	"ABS", from CRT monitors
19	C	30.10.2015	1000	1.9	2361	"ABS", from CRT monitors

*Assuming an average weight of 0.8 grams per flake, as calculated for n=660 flakes from various samples

**Quotation marks indicate information given by recycler which could not be verified in the field

4.3.1 DENSITY SEPARATION OF SAMPLES

4.3.1.1 Method

A two-step density separation was performed on plastic samples in shredded form (flakes), with the following target densities:

1. Density of $1 g/cm^3$ using freshwater: used to separate lighter plastics (e.g. PP, PE) and foreign materials (e.g. foam, paper);
2. Density of $1.1 g/cm^3$ using saltwater at 25°C with 150 grams of salt per litre of water (i.e., 13.6wt% NaCl): used to separate BFR-rich and BFR-poor fractions.

The relations between salt content, water density, and plastic densities were presented in Section 2.3.8.

For each sample, the following procedure was applied:

1. Immersion of samples into saltwater tank, thorough mixing;
2. Removal of fraction sinking in saltwater, kept separately (sub-sample C);
3. Immersion of fraction floating in saltwater into freshwater tank;
4. Removal of fractions sinking and floating in freshwater, both kept separately (sub-samples B and A, respectively);
5. Washing and drying of sub-samples;
6. Weighting of sub-samples

Figure 18: Drying of sub-samples after two-step density separation

4.3.1.2 Results

The two-step density separation produced 45 sub-samples out of the 15 original samples. The weight ratios of A, B, C fractions (sub-samples) for each sample are displayed in Figure 19.

A first observation is that for all samples, the A fraction (floating in freshwater) is very small (max: 6%), indicating that upstream manual separation methods to segregate fractions with density lower than ABS/HIPS are quite effective. In particular, this suggests an efficient segregation of PP and PE from ABS and HIPS, which is noteworthy considering that PP is the third most used polymer in EEE (Maris et al., 2015; Wäger et al., 2010a). A closer look reveals that the fraction of each sample that floats in freshwater is mostly made of small plastic parts containing air bubbles, foams, stickers, and dust (mostly plastic dust).

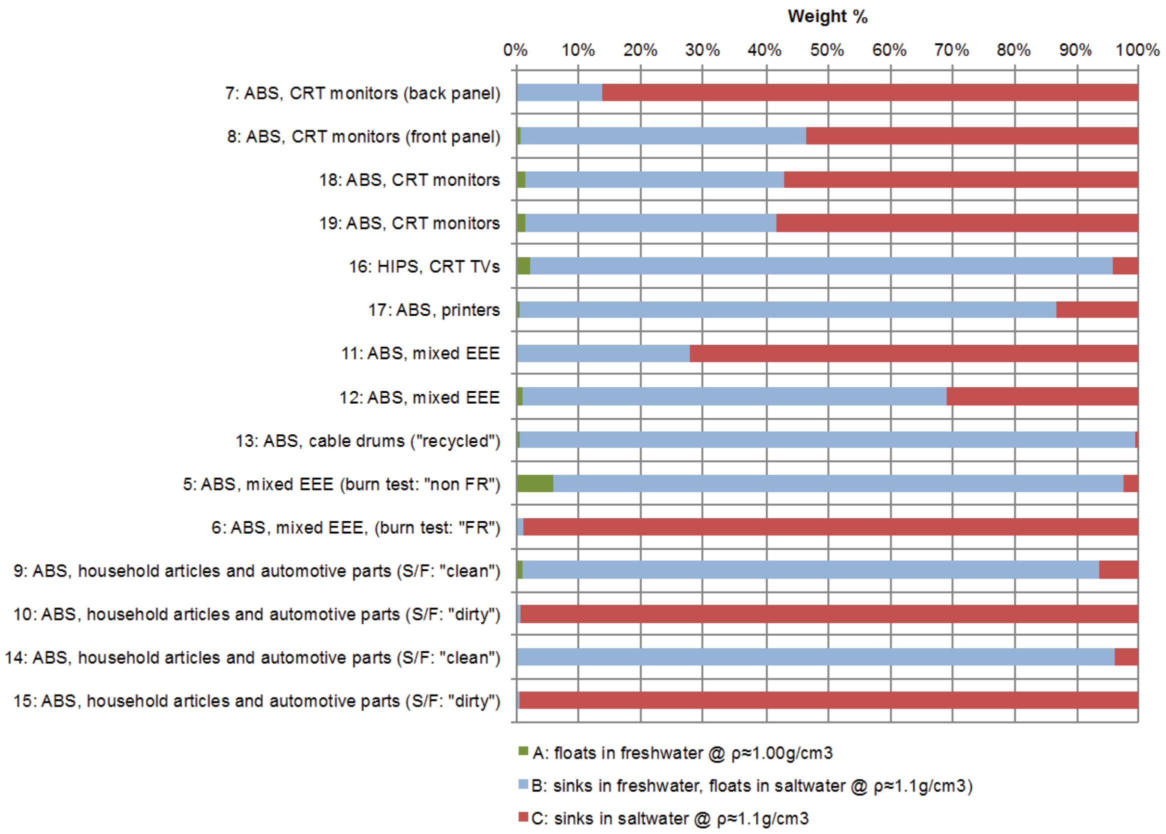


Figure 19: Density distribution of samples

As far as the distribution of B and C fractions (i.e. floating or sinking in saltwater with a target density of 1.1g/cm^3), considerable variations can be observed among samples. Extreme variations exist between samples 5 & 6, 9 & 10, and 14 & 15, that is, samples that previously underwent separation by recyclers, either through burn test (to segregate "non FR" and "FR" fractions) or density separation (to segregate "clean" and "dirty" fractions). This suggests that (i) the burn test is effective to separate plastics containing density enhancer additives such as flame retardants and (ii) the density used by recyclers to "clean" heterogeneous plastic scrap from household articles and automotive parts is close to that used in our trials (although probably higher as 4-6% of the "clean" fraction sinks in saltwater @ 1.1g/cm^3). Samples of ABS from CRT monitors (samples 7,8, 18, 19) contain high shares (58-86%) of flakes sinking in saltwater @ 1.1g/cm^3, which could reflect high shares of BFR plastics in those plastic fractions, in accordance with findings from previous studies (Wäger et al., 2010a). Samples 11 and 12, made of ABS from mixed EEE, contain respectively 72% and 31% of flakes sinking in saltwater @ 1.1g/cm^3, which could be explained by the presence of BFR plastics in significant proportion. Sample of HIPS from CRT TVs (sample 16) contain a low share of plastics sinking in saltwater, suggesting that most of the flakes are BFR-free, which is in accordance with findings from Schlummer et al. (2007). ABS from printers (sample 17) contains a relatively low share of flakes sinking in saltwater. Results of previous studies contrast over the share of BFR plastics in printers (ENVIRON Australia, 2013; Wäger et al., 2010a). Lastly, ABS from cable drums (sample 13), supposedly made from recycled plastics, is almost exclusively contained in the B fraction. This suggests that this sample does not contain BFRs or other density enhancer additives in significant concentrations.

In the absence of information over the bromine content of different sub-samples, no conclusions can be drawn on the effectiveness of saltwater separation to segregate BFR plastics. While semiquantitative and quantitative methods such as XRF are needed to reveal bromine concentrations, a simple qualitative method such as the Beilstein test could be very useful as a screening tool for BFR plastics.

4.3.2 BEILSTEIN SCREENING

4.3.2.1 Method

This simple chemical test, described in in Section 2.3.3, can reveal the presence of halogens in plastics, with a limit of detection estimated at between 0.5% and 1% halogen content. The presence of halogens other than bromine is not to be expected in ABS and HIPS used in EEE, so that a positive Beilstein test on the samples can reasonably be assumed to indicate the presence of BFRs.

As this method is relatively time-intensive (about 5 seconds/flake), and could be associated with health hazards, it was decided not to perform the Beilstein test on all flakes from all sub-samples. Rather, a limited amount of randomly selected flakes from each sub-sample was tested. Based on statistical considerations (Table 9), this limited amount was set at 20 flakes. Given that flakes were pre-sorted according to their bromine content (through density separation), testing 20 flakes only is considered as reliable enough to determine whether a sample if BFR-rich or BFR-poor.

Table 9: Probability of negative Beilstein test (i.e., no green flame) depending on number of flakes tested and distribution of whole sample

	Percentage of Flakes containing Br in total sample														
	0%	5%	10%	15%	20%	30%	40%	50%	60%	70%	80%	85%	90%	95%	100%
Prob. of No Green Flame in 10 Flakes	100%	60%	35%	20%	10%	3%	1%	0%	0%	0%	0%	0%	0%	0%	0%
Prob. of No Green Flame in 20 Flakes	100%	36%	12%	4%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Prob. of No Green Flame in 30 Flakes	100%	21%	4%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Prob. of No Green Flame in 50 Flakes	100%	8%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

Beilstein screening was performed on all sub-samples except those belonging to the A fraction (floating in freshwater) and those representing less than 1% of the weight of their original sample (i.e. sub-samples 6B (0.8%), 13C (0.5%), 10B (0.6%), 15B (0.4%)). As a result, out of the 45 sub-samples, 26 underwent Beilstein screening.

The Beilstein test was conducted in dark and well ventilated conditions, using a simple butane lighter and a 28 gauge copper wire (∅=0.32 mm). The copper wire was heated in the flame until glowing and brought into contact with a plastic flake, after which it was held again in the flame. A green flame indicates the presence of halogens and was characterized as positive Beilstein test.

4.3.2.2 Results

Beilstein screening results show sharp contrasts between sub-samples (Figure 20). Three categories can be distinguished:

1. Plastics from CRT and mixed EEE plastics, sinking in saltwater @ 1.1g/cm^3 (sub-samples 5C, 6C, 7C, 8C, 11C, 12C, 16C, 18C, 19C): more than 65% of tested flakes are Beilstein-positive, indicating a high halogen content (most likely BFRs) in sub-samples;
2. Plastics from printers, mixed household articles and automotive parts, sinking in saltwater @ 1.1g/cm^3 (9C, 10C, 14C, 15C, 17C): 0-30% of tested flakes are Beilstein-positive. This can indicate the presence of plastic types with higher density (e.g. PC, PVC), of non-halogenated density enhancing additives and/or of BFRs below the Beilstein test detection limit in sub-samples;
3. Plastics from various products, floating in saltwater @ 1.1g/cm^3 (5B, 7B, 8B, 9B, 11B, 12B, 13B, 14B, 16B, 17B, 18B, 19B): 0% of tested flakes are Beilstein-positive, indicating a low halogen content in sub-samples.

These results suggest that density separation using a saltwater solution with 13.6% NaCl is effective to separate halogen-rich and halogen-poor ABS/HIPS fractions. This apparent removal efficiency is particularly striking for plastics from CRT and mixed EEE, where more than 65% of the tested flakes from the sinking fraction are Beilstein-positive, and 100% of the tested flakes from the floating fraction are Beilstein-negative. As far as plastics from printers, mixed household articles and automotive parts are concerned, the relatively low share of Beilstein-positive flakes in the sinking fraction indicate that other parameters account for the higher density, such as the presence of higher density plastics, other additives, or BFRs below the Beilstein test detection limit.

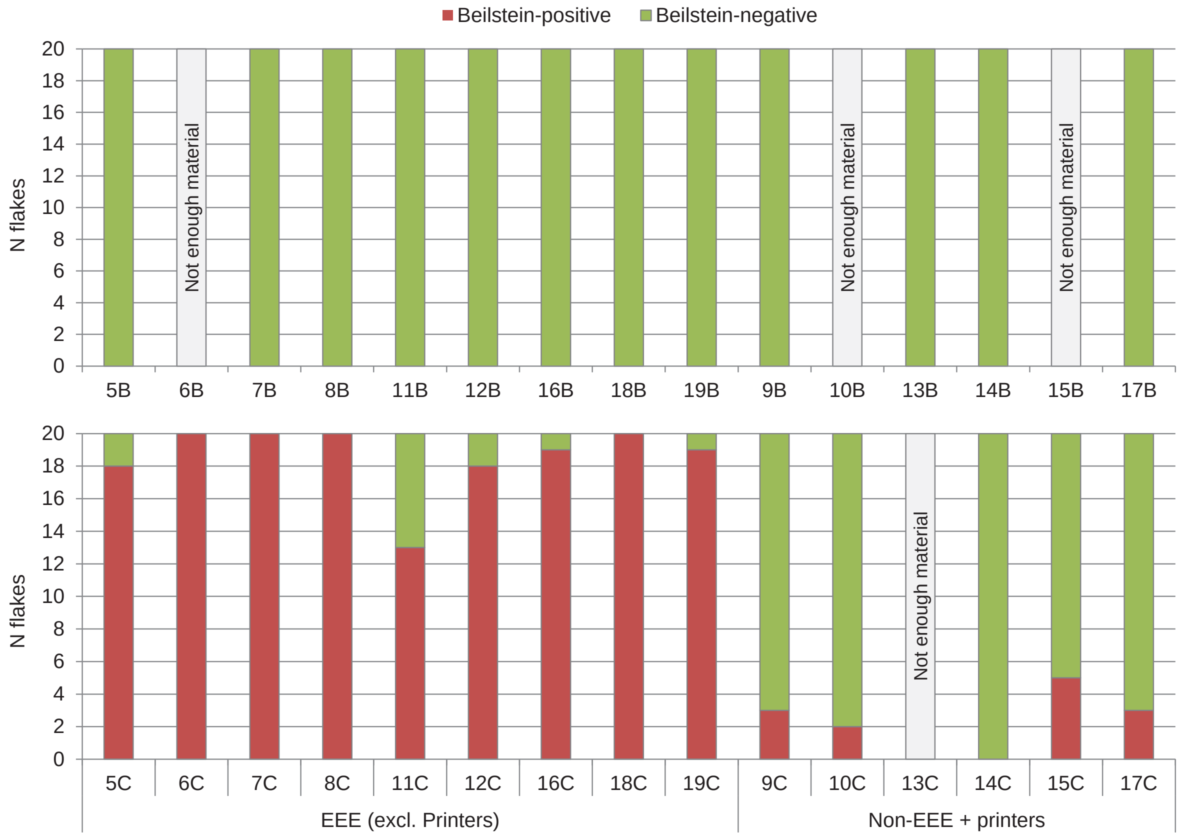


Figure 20: Results of Beilstein screening

In order to reveal what could account for the sinking behaviour of Beilstein-negative flakes, as well as quantify how BFR-free the floating fraction really is, elemental analysis performed in laboratory conditions is required.

4.3.3 LABORATORY SAMPLES PREPARATION AND SELECTION

Prior to the laboratory analyses, the sub-samples were cleaned of non-polymeric materials (metal, rubber, paper, foam, textile, glass, rocks, etc.) and, if weighting more than 1.5kg, reduced in size using the coning and quartering method (Figure 21). In case of reduction by coning and quartering, the remaining fraction was kept as duplicate. Two samples of "dirty ABS" sinking in saltwater @1.1g/cm^3 (samples 10C and 15C), containing a very heterogeneous mixture of polymeric and non-polymeric materials, were further divided into "sub-sub-samples": a plastic fraction (10C(P), 15C(P)), a metal fraction (10C(M), 15C(M)), a plastic-metal fraction (10C(P-M), 15C(P-M)), and a mixed fraction (10C(mix), 15C(mix)).

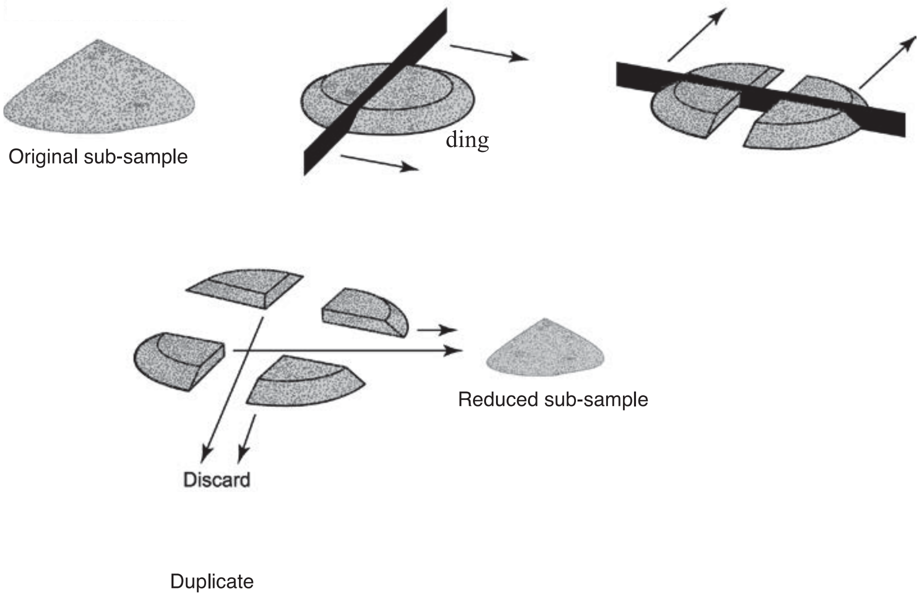


Figure 21: Coning and quartering method (adapted from (Gerlach and Nocerino, 2003))

A list of all sub-samples, including duplicates, is given in Annex C. In total, the original 15 samples were segregated into 60 sub-samples:

- 14 sub-samples A (in one sample, nothing floated in freshwater)
- 15 sub-samples B
- 15 sub-samples C (including 10C(P) and 15C(P))
- 10 duplicates
- 6 "sub-sub-samples" from 10C and 15C sub-samples

Of those 60 sub-samples, 31 were selected to undergo analysis by instrumental methods, on the basis of their weight (18 samples <60g were not analysed) and other criteria (5 duplicates were not analysed, "sub-sub-samples" except the plastic fraction were not analysed).

The 31 laboratory samples (hereafter designated as "samples") have an average weight of 0.7kg (0.07-1.2kg). Each is made of several hundreds of plastics flakes of size between 10 and 50mm (average flake weight is 0.8g).

4.3.4 ELEMENTAL ANALYSIS

Elemental analysis of sub-samples was performed at the Centre for Materials for Electronics Technology (C-MET) – RoHS laboratory, Hyderabad. It is an ISO 17025 accredited laboratory, established as the only Government-owned RoHS testing facility in India.

4.3.4.1 Method

Prior to analyses, the grain size of each sample was reduced to an average size of 1mm using a cutting mill. After homogenization of the powders, each sample was analysed by EDXRF (Energy Dispersive X-ray Fluorescence) to measure bromine (Br) levels with a detection limit of 20ppm. Furthermore, each sample was analysed by ICP-OES (Inductively Coupled Plasma Optical Emission Spectrometry) for the quantification of ten elements (Cr, Cd, Pb, Sb, Mg, Al, Si, P, Ca, Ti) that are either (a) regulated by RoHS, (b) commonly found in flame-retarding compounds, or (c) often used in filler formulations. Finally, each sample was analysed by IC (Ion-Chromatography) to measure Chlorine (Cl) levels. Elements targeted by the elemental analyses are listed in Table 10.

Table 10: Tracers of substances regulated by RoHS or commonly found in flame retardant or filler formulations (adapted from Maris et al. 2015)

Tracer	Flame retardants	Fillers	RoHS Substances	Instrumental method
Br	PBBs, PBDEs, TBBPA		X	EDXRF
Cr			X	ICP-OES
Cd			X	ICP-OES
Pb			X	ICP-OES
Sb	Antimony oxide			ICP-OES
Mg	Magnesium hydroxide	Magnesium silicate		ICP-OES
Al	Aluminium trihydroxide	Aluminium silicate		ICP-OES
Si		Glass fibre		ICP-OES
P	Triphenyl phosphate, bis(diphenyl phosphate, etc.			ICP-OES
Ca		Calcium carbonate		ICP-OES
Ti		Titanium oxide (also used as white pigment)		ICP-OES
Zn	Zinc borate, zinc oxide			ICP-OES
Cl	Chlorinated phosphate			IC

4.3.4.2 Results

Maximum, median, and minimum concentrations of targeted elements found in the 31 samples are displayed in Figure 22. Median concentrations found in samples floating in saltwater @ 1.1g/cm^3 (14 samples, hereafter referred to as "floating samples") and in samples sinking in saltwater @ 1.1g/cm^3 (17 samples, hereafter referred to as "sinking samples") are shown in Figure 23.

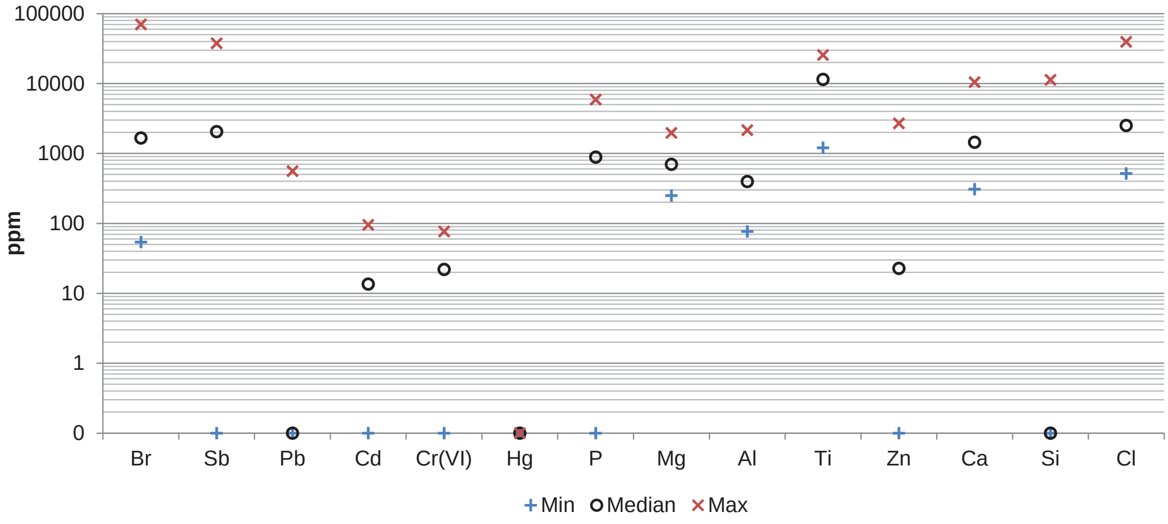


Figure 22: Concentration ranges of targeted elements in 31 samples (both sinking and floating samples)

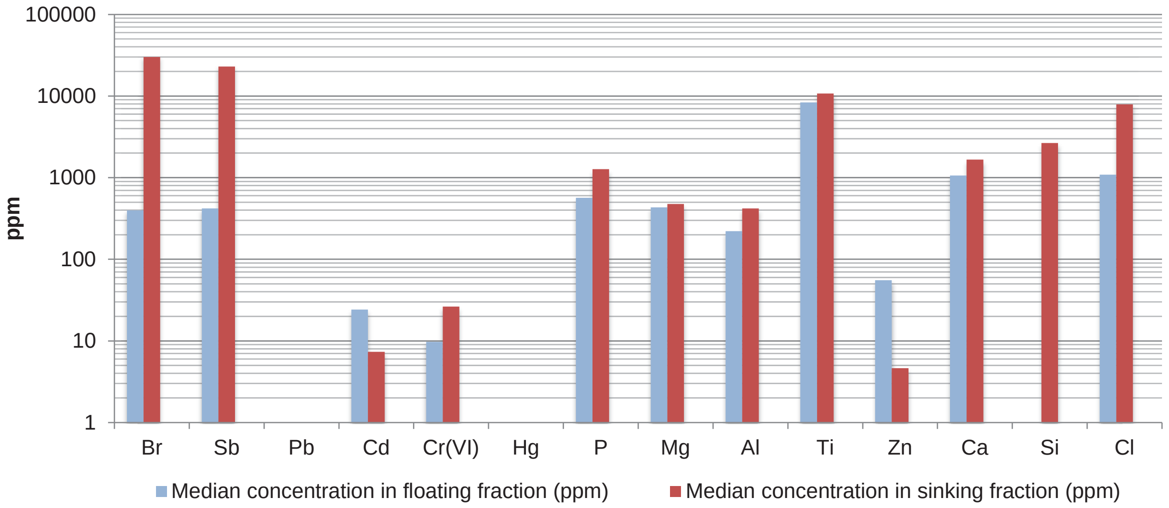


Figure 23: Median concentrations of targeted elements in fraction floating in saltwater @ 1.1g/cm^3 (B samples) and fraction sinking in saltwater @ 1.1g/cm^3 (C samples).

Bromine (**Br**) concentrations were found to range from 54ppm (17B: ABS, printers) up to 68000ppm (8C: ABS, CRT monitors (front panel), 6.8%), with a median of 1600ppm (0.2%) among all samples. A stark contrast can be seen in Br levels measured in floating and sinking samples. A median concentration of 400ppm Br is found in the floating fraction, whereas it rises to 30000ppm Br in sinking samples (factor of 75). Those results indicate that density separation is very effective to separate BFR plastics.

As far as antimony (**Sb**) is concerned, a median concentration a median concentration of 2000ppm (0.2%) was measured. Here also, large variations can be seen between floating and sinking fractions, with a respective median of 420ppm Sb and 23000ppm (2.3%) Sb (factor of 55). Antimony trioxide (Sb_2O_3) is almost always used as a synergist with brominated flame retardants used in ABS and HIPS, with a typical Sb_2O_3 content of 3-5% in BFR plastics (Freegard et al., 2006), i.e. 2.5-4.2% Sb. The median Sb content found in sinking samples (2.3% Sb) is slightly lower than this range.

Chlorine (**Cl**) can be used in chlorinated flame retardants in ABS (Maris et al., 2015). Furthermore, chlorine can originate from PVC or as residue from saltwater separation (using NaCl). Chlorine concentrations range between 520ppm and 37000ppm (3.7%) in samples, with a median of 2000ppm. The median concentration in sinking samples is 7 times higher than in floating samples (8000ppm and 1100ppm), suggesting an influence on the floating behaviour. Chlorine concentrations are highest in ABS plastics from CRT casings, which could be due to the use of chlorine-based flame retardants or to contamination by PVC.

As far as the heavy metals regulated by RoHS are concerned (**Pb**, **Cd**, **Cr(VI)**, **Hg**), concentrations were relatively low in all samples (maximum value below 1000ppm for Pb, 100ppm for Cd and Cr(VI), and below detection limit for Hg). Due to these low concentrations, these elements do not influence density separation and can be found in similar levels both in the floating and sinking fractions. Highest concentrations of lead (560ppm) were found in the floating fraction of ABS used in cable drums, made of recycled plastics according to the recycler from which it was collected (sample 13B).

The presence of non-halogenated flame retardants, such as phosphorus-based FRs (PFRs), magnesium hydroxide, aluminium hydroxide or zinc borate can be indicated by the levels of **P**, **Mg**, **Al** and **Zn**. Of those four elements, phosphorus was found in the highest median concentrations (median: 885ppm, maximum: 5000ppm), followed by magnesium (median: 450ppm, maximum: 1300ppm), aluminium (median: 320ppm, maximum: 1800ppm) and zinc (median: 20ppm, maximum: 2700ppm). In all cases, concentrations observed are too low to achieve flame retardancy. Given that those non-halogenated flame retardants are rarely used in ABS and HIPS (Weil and Levchik, 2009), these low levels suggest that the sorting of plastics by type is quite effective. Relatively small differences exist between median concentrations of P, Mg, Al and Zn and floating and sinking fractions, suggesting that those elements did not play an important role in the density separation.

Magnesium and aluminium can also occur in plastics as mineral fillers, such as magnesium silicate and aluminium silicate. Similarly, compounds containing **Ti**, **Ca** and **Si** (e.g. titanium dioxide, calcium carbonate, fibre glass) can be added to plastics as fillers. Of these filler tracers, Ti was found at the highest concentrations (median: 10000ppm, maximum: 14000ppm). Besides filling function, titanium dioxide serves as white pigment in ABS (Maris et al., 2015). As a result, Ti levels range between 5500ppm and 14000ppm (median: 12000ppm) in grey plastics (20 samples), and between 1200ppm and 4800ppm (median: 2094ppm) in black plastics (11 samples). Ca and Si were also found in significant concentrations (medians: 1100ppm Ca; 0ppm Si, maxima: 9000ppm Ca, 11000ppm Si). Median Ti and Ca levels are 1.3 and 1.6 times greater in sinking samples, respectively. Si occurred below detection level in all floating samples, as well as in four sinking samples. In the remaining eleven sinking samples Si was measured between 500ppm and 11000ppm. Therefore, all of those filler (or pigment) tracers could play a role in the floating behaviour of flakes, but lesser than that of bromine and antimony.

4.4 DISCUSSION

4.4.1 ELEMENTAL CONCENTRATIONS IN ORIGINAL SAMPLES

In order to estimate the concentrations of Br, Sb, Pb, Cd, Cr(VI), Mg, Al, Si, P, Ca, Ti and Cl in the samples originally collected (i.e., 15 samples before density separation), simple mass balances can be done.

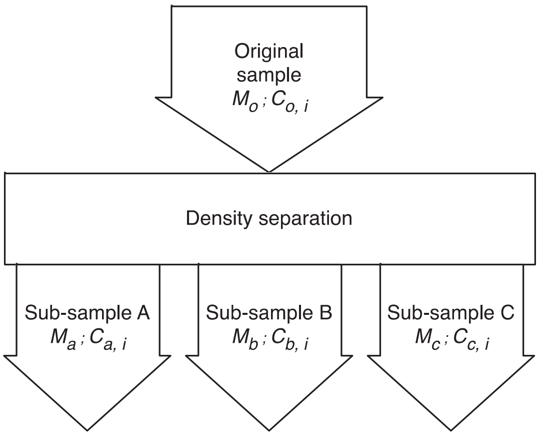


Figure 24: Relations between original sample and sub-samples A, B and C. Each sample can be characterized by its mass (M_a ; M_b ; M_c) and its concentration in element *i* ($C_{a,i}$; $C_{b,i}$; $C_{c,i}$).

Each sample *x* can be characterized by its total mass (M_x), in kg, and its concentration in element *i* ($C_{x, i}$), in mg/kg (ppm). The subscripts *o*, *a*, *b* and *c*, are used to refer, respectively, to the original sample, the sub-sample A (floating in freshwater), the sub-sample B (sinking in freshwater, floating in saltwater with density of 1.1g/cm^3), and the sub-sample C (sinking both in freshwater and in saltwater with density of 1.1g/cm^3). Hence, by mass balance:

$$M_o \times C_{o,i} = M_a C_{a,i} \times M_b C_{b,i} \times M_c C_{c,i}$$

Where *i* = Br, Sb, Pb, Cd, Cr(VI), Mg, Al, Si, P, Ca, Ti, Cl.

The concentration of element *i* in the original sample ($C_{o, i}$) is therefore:

$$C_{o,i} = \frac{M_a C_{a,i} \times M_b C_{b,i} \times M_c C_{c,i}}{M_o}$$

Out of the 45 sub-samples created by density separation, only 26 were characterized by elemental analysis. The remaining 19 sub-samples were not included due to their low size; all excluded samples weight less than 40g and represent less than 2.2% of the original sample except one sample (5A: 130g, 6% of original sample). For the mass balances, the concentrations of elements in those sub-samples that were not analysed are assumed to be negligible.

The concentrations of each element targeted by elemental analyses in the original samples were estimated using the above-mentioned relations. The results are displayed in Figure 25.

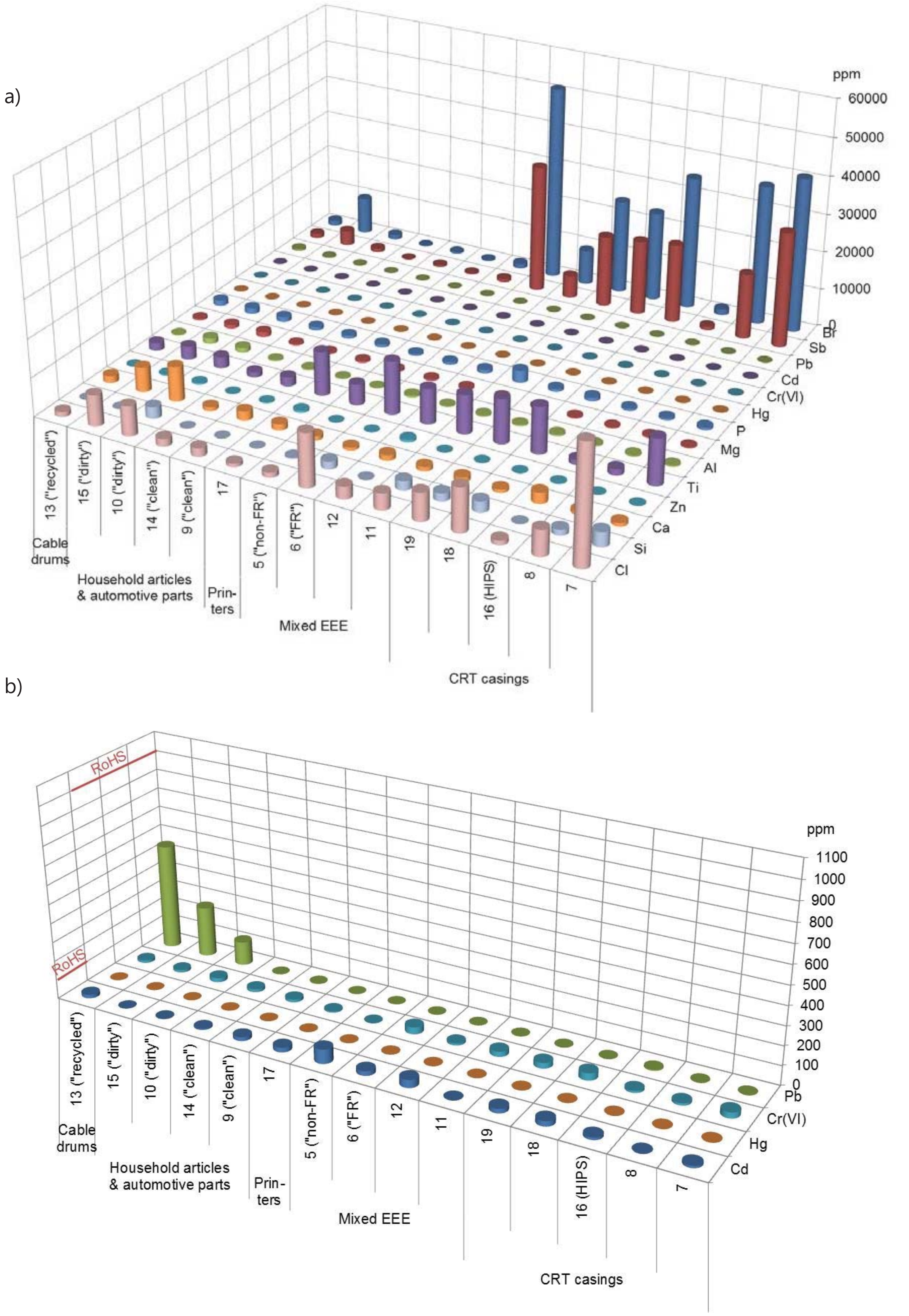


Figure 25: Concentrations of a) target elements, b) heavy metals, in samples originally collected (approximated by mass balances). RoHS MCVs are indicated in red.

As expected, highest bromine and antimony levels are found in ABS samples from CRT casings and mixed EEE, due to the widespread presence of brominated flame retardants in those plastic fractions. Low Br and Sb concentrations are found in samples of ABS from mixed household articles, automotive parts, and cable drums, indicating a low share of BFR plastics in those streams. Concentrations of lead, cadmium, hexavalent chromium and mercury are below RoHS limit values in all original samples. Titanium concentrations are strongly related to the colour of the flakes. Ti levels are much higher in samples mostly made of white/grey plastics (samples 5, 6, 7, 11, 12, 17, 18, 19) than in samples mostly made of black plastics (samples 8, 9, 13, 14, 15, 16). Calcium levels tend to be higher in the sinking fraction of household articles and automotive parts, which indicates the presence of plastics filled with calcium carbonate. Si, Zn, Al, Mg and P levels are low in all samples, and can therefore be expected to have an insignificant influence on the density of plastics (and thus on the sink/float behaviour of flakes). Chlorine is found in higher concentrations in ABS samples from CRT casings and mixed EEE, possibly due to the presence of chlorinated flame retardants. Relatively high levels are also found in "dirty" plastics from household products and automotive parts, which could be due to the presence of PVC in this highly heterogeneous fraction.

4.4.2 COMPARISON WITH PREVIOUS STUDIES

In the past, several studies have been conducted on the elemental composition of WEEE plastics, generally with a broader scope than the current study in terms of polymers analysed (APME, 1997; Dimitrakakis et al., 2009; Fink et al., 2000; Maris et al., 2015; Morf et al., 2007; Schlummer et al., 2007; Stenvall et al., 2013; Vehlow and Mark, 1997; Wäger et al., 2010a). The results from a selection of those studies are compared with those of the current study in Table 11. Furthermore, comparisons with selected results from Wäger et al. (2010b) are displayed in Figure 26. It must be noted that those studies had different methodological approaches, ranges of polymers analysed, and input feeds for samples. As the type and level of additives added to plastics strongly depends on the plastic types as well as on the application, it is not surprising that considerable variations exist in the concentrations of selected elements in WEEE plastics (factor of up to 4000 for Br, between 3 and 2000 for other elements). Any comparisons with a hypothetical "typical" elemental composition of plastics must therefore be done with caution.

Overall, most of our results fall within the ranges of formerly measured concentrations, except for two elements (Mg, Al) where our own highest single value is greater than the maximum levels reported in the reference studies, and one element (P) where own lowest single value is below minimum levels found in the selected literature (Table 11.)

Bromine levels were comparable with those found in the literature, with a maximum content of about 5% Br in heterogeneous WEEE plastic samples (Schlummer et al., 2007; Vehlow and Mark, 1997; Wäger et al., 2010a). Confirming previous findings, bromine levels are the highest in ABS from CRT housings. As shown in Figure 26, median Br concentrations in WEEE streams are very close to those measured by Schlummer et al. (2007) – around 3% in housing plastics and 1.5% in mixed WEEE plastics – but twice as high as results from Wäger et al., (2010a). Longer product lifetimes in India could explain similarities in BFR content with older European plastics. Low Br concentrations were found in HIPS from CRT TVs (sample 17), which corresponds to observations by Schlummer et al. (2007) that HIPS used in TV sets is mostly BFR-free.

Antimony levels found in our study fall in the higher range of the previously reported results, with higher mean and maximum values than in all previous studies except that from Fink et al. (2000). Given its use as a synergist for BFRs, its concentrations tightly linked to Br. As previously mentioned, antimony trioxide is mostly used in combination with BFRs for its synergetic effects, with a typical Sb_2O_3 content of 3-5% in BFR plastics (Freegard et al., 2006), i.e. 2.5-4.2% Sb, and a ratio of Sb_2O_3 to BFR typically lying between 0.25 and 0.5 (Morf et al., 2003). Wäger et al. (2010b) observed a wide range of Sb:Br ratio, from 0.07 up to 0.33. In our case, the Sb to Br ratio in original samples ranges between 0.8 and 2.4, with an average of 1.4. This is considerably higher than previously observed, which could either indicate than antimony concentrations are systematically overestimated and/or bromine levels systematically underestimated. Considering that bromine concentrations correspond to earlier studies, it is most likely that antimony concentrations are systematically biased upwards.

RoHS **heavy metal** concentrations (Pb, Cd, Cr(VI), Hg) tend to be lower than reported in previous studies, especially for lead and chromium. Whereas no samples show level of those substances above RoHS MCVs, significant shares of samples above these limits were found in several reference studies. However, it has been shown that high lead concentrations can be due to contamination from metals fractions and/or thermosets used in PCBs during mechanical shredding in WEEE recycling plants (Wäger et al., 2010a). Such contamination process is unlikely to happen in informal setting where manual dismantling is the norm. The highest cadmium concentration (75ppm), found in "non-FR" ABS from mixed (sample 5), is close to the RoHS MCV (100ppm).

Phosphorus is mostly used in flame retardants added to PC/ABS blends, and rarely (if not never) used in ABS and HIPS (Morgan and Wilkie, 2014), which probably explains why the values found in our samples are lower than reported in previous studies of broader scope in terms of plastic types. Residual concentrations could be caused by the contamination of PC/ABS plastics in the samples, relatively difficult to sort from ABS.

Chlorine concentrations in our results range between 0.1-3%, in line with measurements reported by Schlummer et al. (2007).

As mentioned above, maximum **magnesium** and **aluminium** levels found in our samples are greater than found in the reference studies. For both elements, the highest concentrations were observed in samples of "dirty" ABS from household articles and automotive parts, which suggests that they occurred as fillers (e.g. magnesium and aluminium silicates). Such non-WEEE plastic fractions were mostly absent from the scope of reference studies, which could account for the deviation.

As far as the remaining selected elements are concerned (Ti, Zn, Ca, Si), measured levels are within the spectrum of previous results. **Titanium** concentrations are higher in samples where white/grey plastics dominate due to the use of TiO_2 as white pigment. Increased **calcium** concentrations were found in ABS from household articles and automotive parts (especially in the "dirty" fraction), applications where $CaCO_3$-filled material is preferably used. **Zinc** and **silicium**, respectively used in flame retardants and fillers were only detected in about half of the samples and in low concentrations.

Table 11: Comparison between own results (for original samples, approximated by mass balance) and those of previous studies

	Own results (mass balance)				Schlummer et al., 2007 (WEEE)			Wäger et al., 2010a (Mixed)			Dimitrakakis et al., 2009 (WEEE)	Morf et al., 2007 (WEEE)	Stenvall et al., 2013 (WEEE)		Maris et al., 2015 (WEEE)		Vehlow and Mark 1997 (WEEE)		APME, 1997 (WEEE)		Fink et al., 2000 (WEEE)	
Element	Min	Mean	Median	Max	Min	Median	Max	Min	Median	Max	Mean	Mean	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Br	253	15808	9106	51319	500	14000	49000	64	4400	55000	5300	–	–	–	–	12000	4300	41000	4200	6800	150	250000
Sb	129	10342	3990	33698	260	2400	7000	8	550	13000	2000	3500	–	–	–	1800	2000	13000	–	–	1000	80000
Pb	BDL	63	BDL	553	150	1200	2500	12	380	7800	34	1900	20	200	20	200	100	2100	127	165	500	1000
Cd	BDL	19	19	75	30	90	130	0.01	14	159	38	160	–	–	–	–	30	240	115	186	200	1000
Cr(VI)	1	19	15	38	60	130	400	4	212	1460	100	900	–	–	–	–	60	380	34	71	–	–
Hg	0	0	0	0	5	15	20	0.01	0.2	8	5.3	0.3	–	–	–	–	–	–	0.3	1.4	–	–
P	497	1029	807	3126	–	–	–	12	0.5	35000	–	–	–	–	–	6900	–	–	–	–	–	–
Mg	272	501	457	1259	–	–	–	–		–	–	–	85	200	85	200	–	–	–	–	–	–
Al	115	442	309	1421	–	–	–	–		–	–	–	100	300	100	300	–	–	–	–	–	–
Ti	1234	6685	5352	13689	–	–	–	–		–	8000		–	–	–	11000	1500	18400	4187	4767	300	90000
Zn	BDL	155	38	676	–	–	–	–		–	–	–	200	800	200	800	–	–	–	–	–	–
Ca	770	2192	1138	8973	–	–	–	–		–	–	–	50	10000	50	10000	–	–	–	–	–	–
Si	BDL	1177	285	3753	–	–	–	–		–	–	–	–	–	–	–	–	–	–	–	–	–
Cl	948	6709	4221	29973	840	8500	37000	–		–	–	8600	–	–	–	2500	1900	11000	–	–	–	–

Concentrations in ppm (mg/kg), BDL: below detection limit

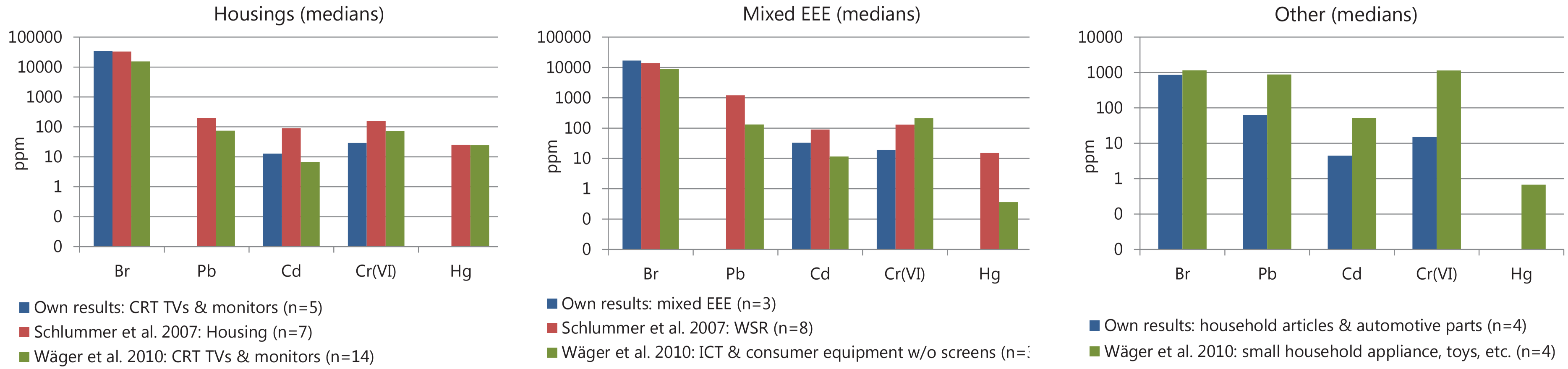


Figure 26: Comparison between selected own results (in original samples) and results for similar categories from (Schlummer et al., 2007; Wäger et al., 2010a)

4.4.3 EFFICIENCY OF DENSITY SEPARATION

As visible in Figure 23, stark contrasts exist between levels of some elements in floating and sinking samples, indicating that the performed density separation effectively segregates fractions that are rich and poor in those elements. The largest variations exist in bromine and antimony levels.

A closer look at the Br content in individual samples (Figure 27) confirms this high removal efficiency. Br content range from 50ppm up to 1400ppm in floating samples (median: 400ppm), and from 1300 up to 68000ppm in sinking samples (median: 28000ppm). All floating samples contain bromine below the 2000ppm level, and therefore comply with the depollution requirements according to the CENELEC standard (CENELEC, 2014).

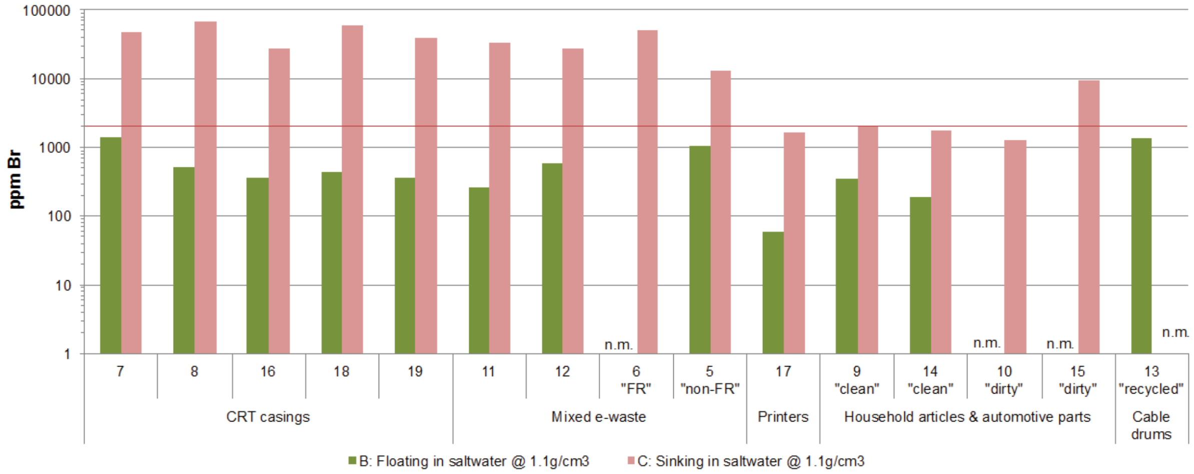


Figure 27: Bromine levels in fractions floating and sinking in saltwater with a density of 1.1g/cm^2. In case of duplicates (6C, 7C, 11C, 12B, 17B), the average value is indicated. Samples 6B, 10B, 15B and 13C were not analysed (n.m.) due to their small size (<20g). The red line indicates the 2000ppm Br level, above which plastics must be treated in facilities capable of removing plastics with BFRs according to the CENELEC standard (CENELEC, 2014).

Knowing the amount of element i in both the original sample before separation ($M_{o,i}C_{o,i}$) and in the sinking fraction after separation ($M_{c,i}C_{c,i}$), it becomes possible to calculate the removal efficiency $\eta_{s,i}$:

$$\eta_{s,i} = 1 - \frac{(M_{c,i}C_{c,i})}{(M_{o,i}C_{o,i})}$$

This formula was used to calculate the removal efficiency for each original sample and for each target element. Results, displayed in Table 12, confirm that the performed density separation was particularly effective to segregate plastics containing bromine and antimony, i.e. BFR plastics. For bromine, the removal efficiency is greater than 95% in cases where bromine was present above 1500ppm in the original sample, but can be as low as 25% in the cases of pre-sorted “non-FR” and “clean” samples (samples 5, 9, 14), where bromine levels were already low before density separation. Taking only in consideration those cases where bromine was present above 1500ppm in the original sample (11 out of 15 cases), an average removal efficiency of 96% is calculated for bromine, and of 95% for antimony.

Results are less straightforward for other elements. Average separation efficiencies range between 40% and 70% for most elements, which is quite low and not much better than random. In this case, it can therefore be concluded that the salt water separation performed on samples was not very effective or not effective at all to separate fractions poor or rich in these other selected elements.

Table 12: Efficiency of density separation using saltwater with ρ=1.1 g/cm^3, for various feeds (original samples) and elements. A removal efficiency of 100% means that the total amount of element i in the original sample was transferred into the sinking fraction, i.e. the separation was very efficient. A removal efficiency of 50% means that only half of the element in the original sample was transferred into the sinking fraction, i.e. the separation was not effective. “HA & AP”: Household articles and automotive parts.

Original sample	Removal efficiency $\eta_{s,i}$													
	Br	Sb	Pb	Cd	Cr	Hg	P	Mg	Al	Ti	Zn	Ca	Si	Cl
5: ABS, mixed EEE ("non FR")	26%	48%	3%	0%	72%	3%	8%	3%	39%	6%	15%	17%	100%	3%
6: FR ABS, mixed EEE ("FR")	100%	100%	99%	100%	100%	99%	100%	100%	100%	100%	99%	100%	100%	100%
7: ABS, CRT monitors (back panel)	100%	99%	86%	70%	87%	86%	90%	88%	96%	87%	86%	95%	100%	98%
8: ABS, CRT monitors (front panel)	99%	98%	53%	1%	48%	53%	58%	46%	57%	58%	53%	55%	100%	95%
9: ABS, HA & AP ("clean")	28%	28%	0%	8%	6%	6%	7%	12%	11%	12%	31%	13%	6%	14%
10: ABS, HA & AP ("dirty*)	100%	100%	100%	100%	100%	99%	100%	100%	100%	100%	100%	100%	100%	100%
11: ABS, mixed EEE	100%	99%	72%	99%	96%	72%	86%	73%	90%	67%	100%	75%	100%	97%
12: ABS, mixed EEE	96%	92%	31%	6%	66%	31%	80%	38%	48%	38%	47%	41%	31%	77%
13: ABS, cable drums ("recycled")	n/a													
14: ABS, HA & AP ("clean")	28%	30%	4%	8%	6%	4%	7%	13%	4%	13%	79%	25%	4%	3%
15: ABS, HA & AP ("dirty")	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
16: HIPS, CRT TVs	77%	73%	100%	2%	20%	4%	13%	13%	2%	5%	11%	11%	4%	13%
17: ABS, printers	81%	87%	13%	14%	50%	13%	21%	22%	27%	17%	63%	40%	13%	20%
18: ABS, CRT monitors	99%	97%	57%	17%	63%	57%	75%	56%	85%	57%	57%	59%	100%	94%
19: ABS, CRT monitors	99%	99%	58%	7%	86%	58%	73%	54%	66%	53%	58%	55%	100%	94%
Average	81%	82%	55%	38%	64%	49%	58%	51%	59%	51%	64%	56%	68%	65%
Average (except pre-sorted samples 13, 5, 9, 14)	96%	95%	70%	47%	74%	61%	72%	63%	70%	62%	70%	66%	77%	81%

The removal efficiency formula can also be used to assess the efficiency of the burn test to segregate BFR plastics, considering the Br levels in samples 5 and 6. Those two samples originated from the same pile but underwent burn test separation operated by the recycler to segregate “FR” and “non-FR” plastics. Assuming a hypothetical “original sample” consisting of the sum of samples 5 and 6, the removal efficiency can be calculated as follows:

$$\eta_s = 1 - \frac{\left(M_{5,Br}C_{5,Br}\right)}{\left(M_{5,Br}C_{5,Br}\right) + \left(M_{6,Br}C_{6,Br}\right)} = 1 - \frac{(2.18kg \times 1300ppm)}{(2.18kg \times 1300ppm) + (2.13kg \times 51300ppm)} = 97\%$$

This suggests that a simple burn test can already be very effective to separate BFR plastics, provided that the stream to be sampled is likely to be BFR rich (in this case, ABS from mixed EEE).

4.4.4 CONSISTENCY OF SIMPLE SEPARATION AND SCREENING METHODS

Equipped with a precise knowledge on the content of different samples in BFRs and other additives, it is useful to look back on the simple separation and screening methods employed to identify and separate BFR plastics in order to assess whether those simple methods can be used to reliably channelize BFR plastics in low-tech environments.

In Figure 28, the results of the density separation (Section 4.3.1) and Beilstein screening (Section 4.3.2) are integrated and compared with the bromine levels revealed by EXDRF (Section 4.3.4). The proportion of Beilstein-positive and Beilstein-negative flakes was multiplied by the weight ratio of each sub-sample in the original sample in order to be displayed.

Samples with a high proportion of flakes sinking are also samples with high bromine levels. In the case of ABS from CRT casings, most of the sinking flakes tested were also Beilstein positive, indicating a high BFR content which is confirmed by EDXRF results. As far as ABS from mixed EEE and printers are concerned, a significant share of sinking flakes tested were Beilstein-negative, indicating that other additives account for the sinking behaviour. For instance, sample 11 comes second in terms of proportion of flakes belonging to the C fraction, but only fourth in terms of total bromine concentration. Relatively high phosphorus and titanium concentrations were observed in this sample, which could provide an explanation. In the case of ABS from household articles and automotive parts, most tested flakes from the C fraction were Beilstein-negative. Relatively high calcium levels were found in the sinking fractions of those streams.

Overall, results show that both density separation and Beilstein screening give results that are consistent with chemical analyses. Density separation using saltwater at a density of 1.1g/cm^3 is very effective to obtain a “clean” fraction, with bromine levels below 2000ppm. The bromine content of the sinking fraction depends on the original feed. It can be expected to be rich in BFRs if the feed is ABS from EEE, but can also be relatively poor in BFRs if the feed is other plastic types and/or ABS used in non flame-sensitive applications such as small household appliances or automotive parts. A screening using the Beilstein test can be very useful to assess the “BFR-richness” of the sinking fraction, as well as to verify on the spot the efficiency of a density separation process.

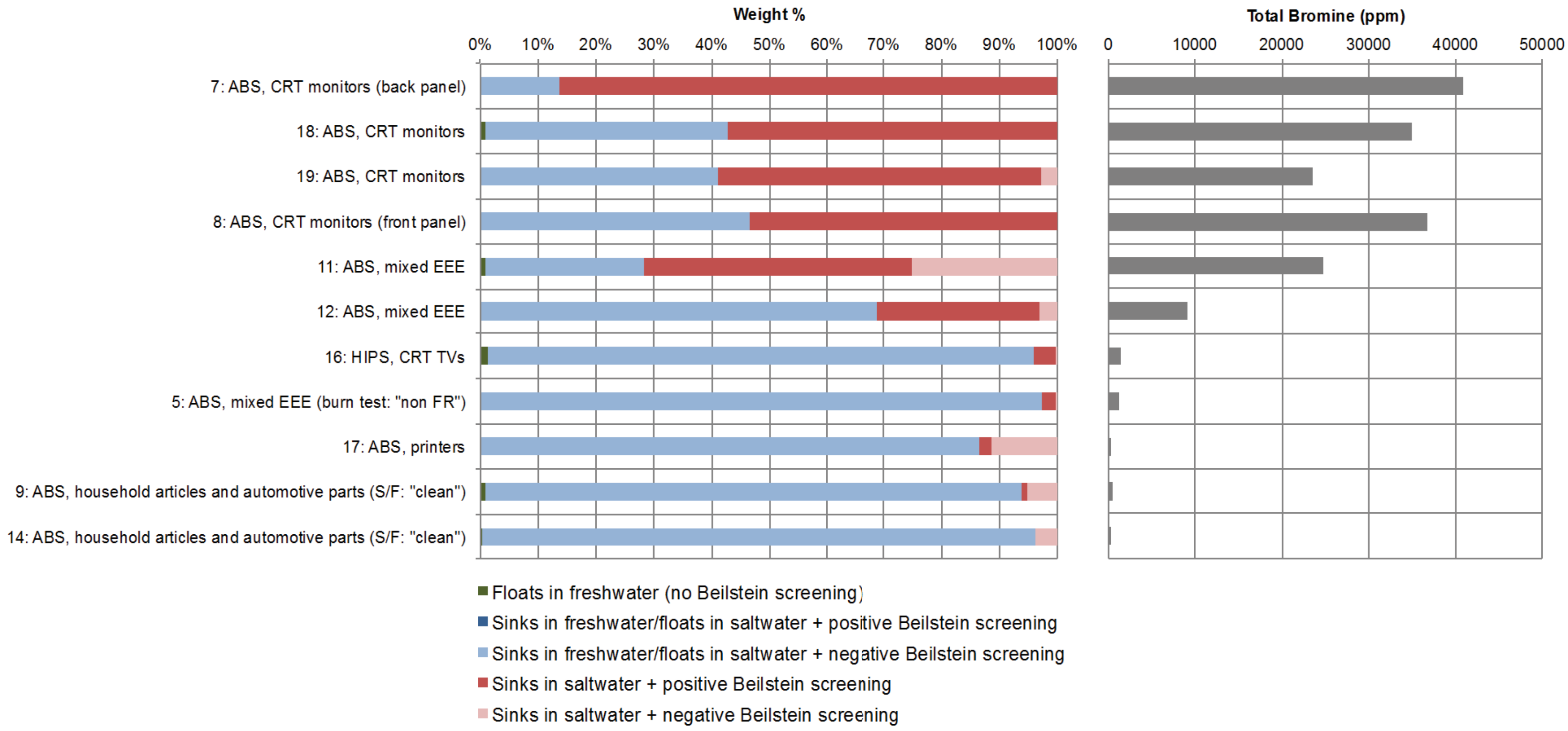


Figure 28: Left: Combination of density separation and Beilstein screening results (only included are samples for which both the B and C fractions were screened using the Beilstein test). Right: Bromine levels in samples according to EDXRF results

4.4.5 UNCERTAINTIES

Out of all the samples sent for laboratory analyses, some can be considered as duplicates in the sense that they came from the same subfraction. These duplicates both represent fractions that float and sink in saltwater and can be used for a simplified estimation of uncertainty (Figure 29). This is a simplified uncertainty assessment, which only gives an indication of the combined uncertainties of sample preparation and instrumental analysis.

Variations are below one order of magnitude in all cases, with the largest variations observed for phosphorus and silicon. Measurements are particularly consistent in the case of bromine, magnesium, titanium, and chlorine levels (variations below a factor of 1.7). This is an indication that both the sampling and analytical procedures were correctly performed to ensure reliable and repeatable results.

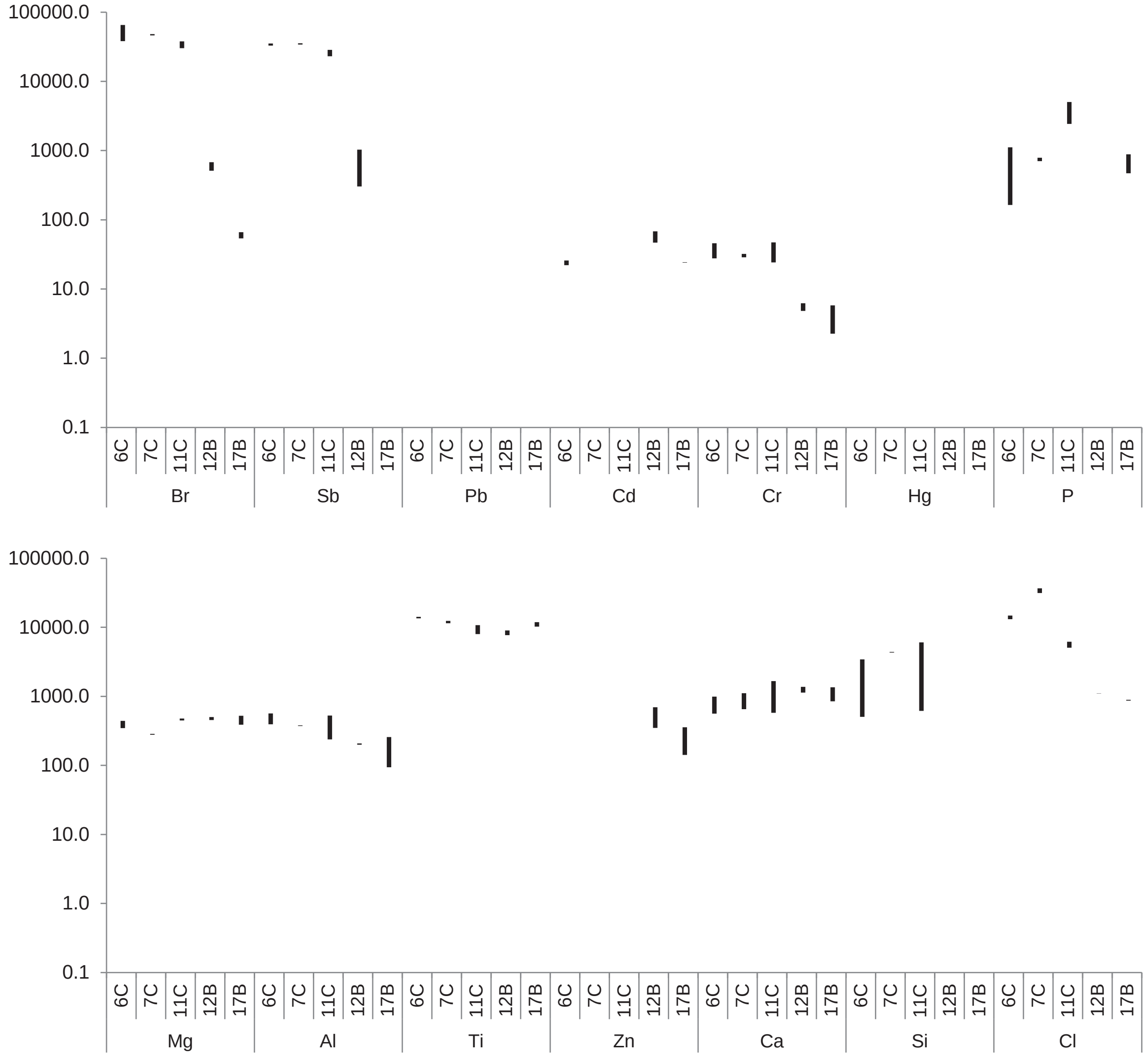


Figure 29: Lower and upper elemental concentrations for samples where a duplicate exist. When lower concentrations are below detection limit, lower and upper concentrations were not displayed.

5 CONCLUSIONS

With the present study, substantial amounts of information were generated on various topics such as the material flows of WEEE plastics in Delhi's informal plastic recycling system, the awareness on and fate of BFR plastics within this system, and the efficiency of various simple methods to separate BFR plastics and therefore "clean" the plastic loop from those hazardous additives.

In particular, the following conclusions can be drawn from the results:

1. Specific channels exist for BFR-rich plastic streams in Delhi's informal recycling system, fulfilling a concentrating function for this potentially hazardous stream. Some of the most BFR-rich fractions, such as casings from CRT TVs and monitors, are seen as particularly attractive for recyclers due to their relative homogeneity and cleanliness. Any efforts to remove BFR plastics from the informal recycling chain will have to identify and tap those channels.
2. As of now, most BFR plastic is not separated as such due to missing incentives and becomes mixed with the mainstream during recycling processes. Simple and potentially effective BFR separation techniques, such as the burn test and the sink/float method, are known of by recyclers specialized in these streams, but are rarely employed due to the lack of market for FR-segregated plastics.
3. Chemical analyses confirmed that some plastic fractions, such as ABS from CRT casings, contain very high levels of BFRs. Due to the slower turnover of materials in developing countries, restricted BFRs can be expected to occur in higher proportions and for a longer time period than in developed nations. A follow-up study is planned to characterize the BFR congeners composition of collected samples, which will allow to draw conclusions on the issues of residence time and occurrence of restricted BFRs in Indian WEEE housings.
4. Levels of heavy metals measured were below regulatory limits (RoHS) in all samples, indicating that the management of those hazardous additives in WEEE plastic recycling facilities is of lower priority than for BFRs.
5. The sink/float, or density separation, method using a solution of freshwater and table salt (with 150g NaCl added per litre of freshwater) was found to be very effective to separate BFR plastics collected in the informal sector, with an average removal efficiency of 96%.
6. The sink/float method can be used in combination with other simple tests, such as the burn test or the Beilstein test, in order to obtain BFR-free plastic fractions. All those methods are inexpensive, simple and robust enough to be used in conditions found in the informal sector. However, only the sink/float method is guaranteed to be free of hazards and should therefore always be preferred.

BFR plastics are currently not properly management in the informal sector, which poses risks for both workers and consumers. It is a requirement for sustainable development that this issue is properly addressed through the implementation of channels to remove BFR plastics from informal recycling units. This study confirms that efficient technologies for BFR-separation are already in use. Hence the factors limiting spread of BFRs into new products are not technological, but organisational Therefore, public and private stakeholders should work together on regulatory, technical and financial aspects on such take back channels. Particular attention should be spent on developing viable financial schemes to support the system, and setting up a monitoring system to ensure its proper functioning.

The results of this study can be used to design and implement separation systems based on the sink/float method. This technique can be performed with enough accuracy using inexpensive containers made of plastic and/or concrete as well as simple table salt. Considering that knowledge of sink/float separation already exists in the informal sector, training in the sink/float separation mechanism is not a-priori necessary. However, field observations also show that the separation could be further improved and its adoption increased by training workers on the specific salt-water formulations to use. In addition, the hazardousness of the material requires that workers in contact with WEEE plastic receive minimum training in health and safety aspects.

Throughout this study, several information gaps were identified and, we believe, deserve special attention for future research in various fields:

- Technological assessment: Scientific studies should be conducted to compare the efficiency of manual plastic sorting methods used by informal recyclers (summarized in Table 5, page 23) with that of technologically sophisticated methods used in industrialized countries (e.g. IR, electrostatic, etc.). The later are not always very effective depending on the input feed due to technical challenges (e.g. similar densities, dark colour hindering IR identification, etc.), and one could imagine that some of the indigenous knowledge developed in the Indian informal sector can be used by recyclers of more technologically advanced countries.
- Polymer science: During field visits, most recyclers requested technical information on how to improve the quality of their output. Technological partnerships with formal institution in India and Switzerland should be fostered in order to develop cost-effective methods to improve the quality of plastics recycled in the informal sector.
- Industrial ecology: During the research, linkages between the informal plastic recycling system and the informal brick manufacturing system were uncovered. Plastics that cannot be recycled anymore are sold as alternative fuel for brick making, which is a huge economic sector in India. Research to trace the fate of hazardous substances during such "informal industrial symbioses" would be of great interest.
- Product design: The Beilstein test was identified as the most inexpensive method to identify BFR plastics. The potential formation of hazardous fumes during testing however prevents us from recommending the implementation of this technique. The design of a simple, safe and inexpensive "Beilstein apparatus" that includes a fume extraction system could enable all recyclers, both in developed and developing countries, to identify BFR plastics.

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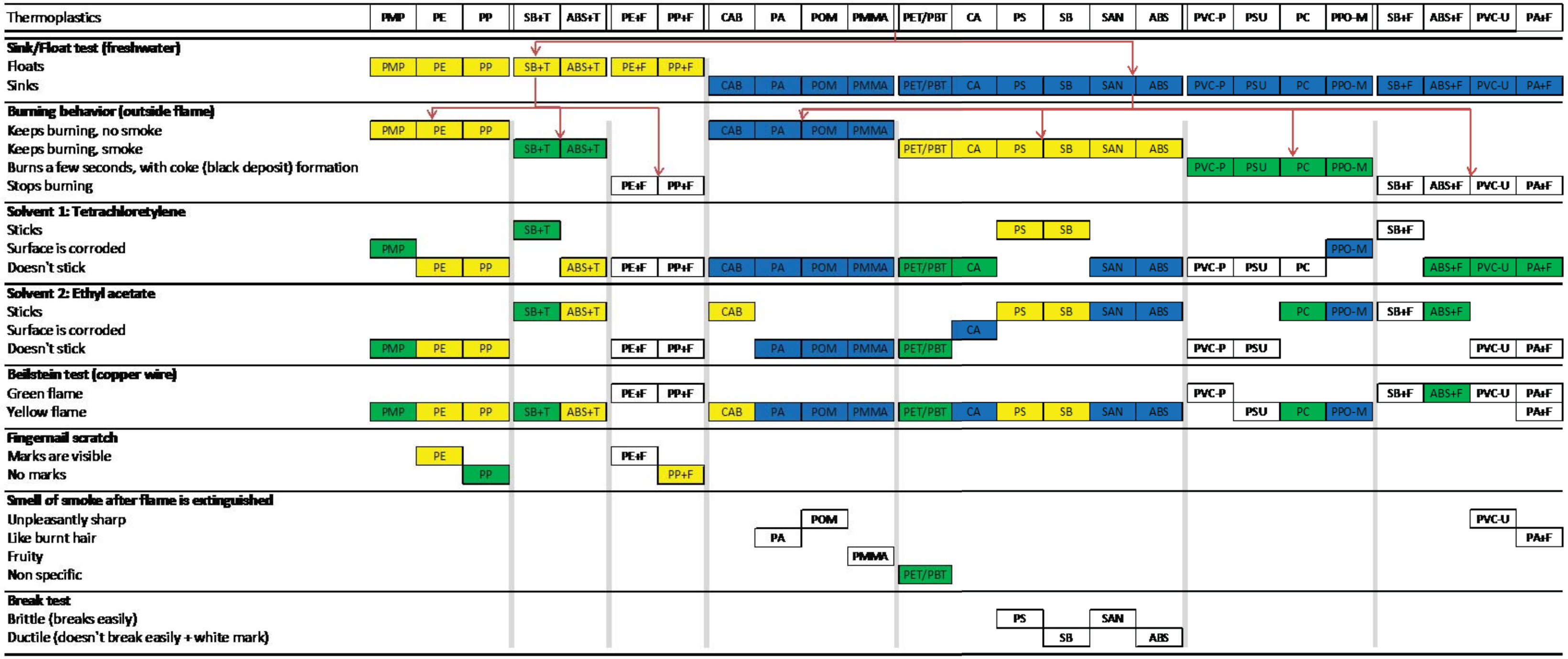
ANNEX A: KATZ POLYMER IDENTIFICATION TREE



Thermoplastics	PMP	PE	PP	SB+T	ABS+T	PE+F	PP+F	CAB	PA	POM	PMMA	PET/PBT	CA	PS	SB	SAN	ABS	PVC-P	PSU	PC	PPO-M	SB+F	ABS+F	PVC-U	PA+F
Sink/Float test (freshwater)																									
Floats	PMP	PE	PP	SB+T	ABS+T	PE+F	PP+F																		
Sinks								CAB	PA	POM	PMMA	PET/PBT	CA	PS	SB	SAN	ABS	PVC-P	PSU	PC	PPO-M	SB+F	ABS+F	PVC-U	PA+F
Burning behavior (outside flame)																									
Keeps burning, no smoke	PMP	PE	PP					CAB	PA	POM	PMMA														
Keeps burning, smoke				SB+T	ABS+T							PET/PBT	CA	PS	SB	SAN	ABS								
Burns a few seconds, with coke (black deposit) formation																		PVC-P	PSU	PC	PPO-M				
Stops burning						PE+F	PP+F															SB+F	ABS+F	PVC-U	PA+F
Solvent 1: Tetrachloretylene																									
Sticks				SB+T										PS	SB							SB+F			
Surface is corroded	PMP																				PPO-M				
Doesn't stick		PE	PP		ABS+T	PE+F	PP+F	CAB	PA	POM	PMMA	PET/PBT	CA			SAN	ABS	PVC-P	PSU	PC			ABS+F	PVC-U	PA+F
Solvent 2: Ethyl acetate																									
Sticks				SB+T	ABS+T			CAB						PS	SB	SAN	ABS			PC	PPO-M	SB+F	ABS+F		
Surface is corroded													CA												
Doesn't stick	PMP	PE	PP			PE+F	PP+F		PA	POM	PMMA	PET/PBT						PVC-P	PSU					PVC-U	PA+F
Beilstein test (copper wire)																									
Green flame						PE+F	PP+F											PVC-P				SB+F	ABS+F	PVC-U	PA+F
Yellow flame	PMP	PE	PP	SB+T	ABS+T			CAB	PA	POM	PMMA	PET/PBT	CA	PS	SB	SAN	ABS		PSU	PC	PPO-M				PA+F
Fingernail scratch																									
Marks are visible		PE				PE+F																			
No marks			PP				PP+F																		
Smell of smoke after flame is extinguished																									
Unpleasantly sharp										POM														PVC-U	
Like burnt hair									PA																PA+F
Fruity											PMMA														
Non specific												PET/PBT													
Break test																									
Brittle (breaks easily)														PS		SAN									
Ductile (doesn't break easily + white mark)															SB		ABS								

Legend

PMP	Polymethylpentene
PE	Polyethylene
PP	Polypropylene
SB+T	Syrene-butadene, impact modified
ABS+T	Acrylonitrile butadiene styrene, impact modified
PE+F	Polyethylene, flame retarded with halogen
PP+F	Polypropylene, flame retarded with halogen
CAB	Cellulose acetate butyrate
PA	Polyamides (nylon)
POM	Polyoxymethylene (=acetal)
PMMA	Polymethyl methacrylate
PET/PBT	Polybutylene/polyethylene terephthalate
CA	Cellulose acetate
PS	Polystyrene
SB	Syrene-butadene
SAN	Styrene-acrylonitrile resin
ABS	Acrylonitrile butadiene styrene
PVC-P	Polyvynil chloride, plasticised (soft)
PSU	Polysulfone
PC	Polycarbonate
PPO-M	Poly(phenylene oxide)
SB+F	Syrene-butadene, flame retarded
ABS+F	Acrylonitrile butadiene styrene, flame retarded
PVC-U	Polyvynil chloride, unplasticised (hard)
PA+F	Polyamides (nylon), flame retarded

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Centre de formation et de technologie des matières plastiques
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Plastics Training and Technology Center

+swiss plastics
The network for the future

Translated by Arthur Haarman, Empa

ANNEX B: SAMPLING CAMPAIGN PICTURES

ANNEX C: LIST OF SUB-SAMPLES

Original sample	Total weight before density separation (g)	Sub-sample	Description	Weight (g)	Sent to laboratory
5: ABS, mixed EEE (burn test: "non FR")	2254	5A	Floating in freshwater	128	Yes
		5B	Sinking in freshwater, floating in water @ 1.1 g/cm3	1030	Yes
		5B*	Sinking in freshwater, floating in water @ 1.1 g/cm3 (duplicate)	992	No
		5C	Sinking in water @ 1.1g/cm3	55	No
6: ABS, mixed EEE, (burn test: "FR")	2132	6A	Floating in freshwater	7	No
		6B	Sinking in freshwater, floating in water @ 1.1 g/cm3	17	No
		6C	Sinking in water @ 1.1g/cm3	1072	Yes
		6C*	Sinking in water @ 1.1g/cm3 (duplicate)	835	Yes
7: ABS, CRT monitors (back panel)	2379	7A	Floating in freshwater	4	No
		7B	Sinking in freshwater, floating in water @ 1.1 g/cm3	332	Yes
		7C	Sinking in water @ 1.1g/cm3	1043	Yes
		7C*	Sinking in water @ 1.1g/cm3 (duplicate)	835	Yes
8: ABS, CRT monitors (front panel)	2238	8A	Floating in freshwater	13	No
		8B	Sinking in freshwater, floating in water @ 1.1 g/cm3	1032	Yes
		8C	Sinking in water @ 1.1g/cm3	1169	Yes
9: ABS, household articles and automotive parts (S/F: "clean")	2145	9A	Floating in freshwater	18	No
		9B	Sinking in freshwater, floating in water @ 1.1 g/cm3	984	Yes
		9B*	Sinking in freshwater, floating in water @ 1.1 g/cm3 (duplicate)	982	No
		9C	Sinking in water @ 1.1g/cm3	130	Yes
10: ABS, household articles and automotive parts (S/F: "dirty")	2291	10A	Floating in freshwater	2	No
		10B	Sinking in freshwater, floating in water @ 1.1 g/cm3	11	No
		10C (mix)	Sinking in water @ 1.1g/cm3 (mixed fraction)	741	No
		10C (P)	Sinking in water @ 1.1g/cm3 (plastic fraction)	742	Yes
		10C (M)	Sinking in water @ 1.1g/cm3 (metal fraction)	192	No
		10C (P-M)	Sinking in water @ 1.1g/cm3 (plastic-metal fraction)	146	No
11: ABS, mixed EEE	2125	11A	Floating in freshwater	3	No
		11B	Sinking in freshwater, floating in water @ 1.1 g/cm3	586	Yes
		11C	Sinking in water @ 1.1g/cm3	834	Yes
		11C*	Sinking in water @ 1.1g/cm3 (duplicate)	590	Yes
12: ABS, mixed EEE	2140	12A	Floating in freshwater	21	No
		12B	Sinking in freshwater, floating in water @ 1.1 g/cm3	757	Yes
		12B*	Sinking in freshwater, floating in water @ 1.1 g/cm3 (duplicate)	669	Yes
		12C	Sinking in water @ 1.1g/cm3	635	Yes
13: ABS, cable drums	2199	13A	Floating in freshwater	12	No

("recycled")		13B	Sinking in freshwater, floating in water @ 1.1 g/cm3	1081	Yes
		13B*	Sinking in freshwater, floating in water @ 1.1 g/cm3 (duplicate)	1066	No
		13C	Sinking in water @ 1.1g/cm3	10	No
14: ABS, household articles and automotive parts (S/F: "clean")	1872	14A	Floating in freshwater	5	No
		14B	Sinking in freshwater, floating in water @ 1.1 g/cm3	925	Yes
		14B*	Sinking in freshwater, floating in water @ 1.1 g/cm3 (duplicate)	872	No
		14C	Sinking in water @ 1.1g/cm3	72	Yes
15: ABS, household articles and automotive parts (S/F: "dirty")	2077	15B	Sinking in freshwater, floating in water @ 1.1 g/cm3	7	No
		15C (mix)	Sinking in water @ 1.1g/cm3 (mixed fraction)	773	No
		15C (P)	Sinking in water @ 1.1g/cm3 (plastic fraction)	782	Yes
		15C (M)	Sinking in water @ 1.1g/cm3 (metal fraction)	87	No
		15C (P-M)	Sinking in water @ 1.1g/cm3 (plastic-metal fraction)	93	No
16: HIPS, CRT TVs	1716	16A	Floating in freshwater	38	No
		16B	Sinking in freshwater, floating in water @ 1.1 g/cm3	827	Yes
		16B*	Sinking in freshwater, floating in water @ 1.1 g/cm3 (duplicate)	777	No
		16C	Sinking in water @ 1.1g/cm3	69	Yes
17: ABS, printers	1574	17A	Floating in freshwater	9	No
		17B	Sinking in freshwater, floating in water @ 1.1 g/cm3	679	Yes
		17B*	Sinking in freshwater, floating in water @ 1.1 g/cm3 (duplicate)	673	Yes
		17C	Sinking in water @ 1.1g/cm3	208	Yes
18: ABS, CRT monitors	1995	18A	Floating in freshwater	26	No
		18B	Sinking in freshwater, floating in water @ 1.1 g/cm3	835	Yes
		18C	Sinking in water @ 1.1g/cm3	1118	Yes
19: ABS, CRT monitors	1889	19A	Floating in freshwater	25	No
		19B	Sinking in freshwater, floating in water @ 1.1 g/cm3	758	Yes
		19C	Sinking in water @ 1.1g/cm3	1062	Yes

ANNEX D: RESULTS OF CHEMICAL ANALYSES

Sub-sample	Sub-sample weight (g)	Short description	Pb mg/kg	Cd mg/kg	Cr(VI) mg/kg	Hg mg/kg	P mg/kg	Mg mg/kg	Al mg/kg	Ti mg/kg	Zn mg/kg	Ca mg/kg	Si mg/kg
05B	1030	5B: ABS, mixed EEE (burn test: "non-FR")	0.0	81.4	0.3	0.0	497.5	549.9	76.9	5501.0	22.6	993.4	0.0
05C	55	5C: ABS, mixed EEE (burn test: "non-FR")	0.0	0.0	26.3	0.0	1622.2	612.6	1753.6	12387.8	140.7	7224.0	11312.4
06C	1072	6C: FR ABS, mixed EEE (burn test: "FR")	0.0	25.8	27.8	0.0	1117.6	346.7	393.8	14203.8	0.0	563.8	506.7
06C*	835	6C*: FR ABS, mixed EEE (burn test: "FR")	0.0	22.1	46.0	0.0	163.5	440.2	565.9	13485.9	0.0	993.2	3438.5
07B	332	7B: ABS, CRT monitors (back panel)	0.0	25.5	29.8	0.0	536.5	255.6	102.4	11826.2	0.0	307.7	0.0
07C	1043	7C: ABS, CRT monitors (back panel)	0.0	18.8	32.2	0.0	786.5	286.1	379.5	12414.3	0.0	652.1	4307.3
07C*	835	7C*: ABS, CRT monitors (back panel)	0.0	0.0	28.7	0.0	706.2	277.8	371.5	11443.1	0.0	1108.7	4389.2
08B	1032	8B, ABS, CRT monitors (front panel)	0.0	1.8	14.1	0.0	483.7	426.4	279.3	1449.9	0.0	836.1	0.0
08C	1169	8C: ABS, CRT monitors (front panel)	0.0	0.0	11.3	0.0	574.2	311.5	320.2	1712.4	0.0	877.8	2658.9
09B	984	9B, ABS, HA & AP ("clean")	3.2	19.8	14.9	0.0	876.3	441.4	258.6	2264.6	134.0	2268.3	0.0
09C	130	9C, ABS, HA & AP ("clean")	0.0	25.9	13.5	0.0	1008.4	889.8	464.6	4832.6	901.9	4928.8	0.0
10C (P)	742	10C: ABS, HA & AP ("dirty*)	125.0	2.0	21.9	0.0	1323.7	1267.7	1223.5	2985.8	408.2	9035.8	3017.2
11B	586	11B: ABS, mixed EEE	0.0	0.0	4.1	0.0	1565.4	446.6	113.8	11966.4	0.0	974.7	0.0
11C	834	11C: ABS, mixed EEE	0.0	0.9	47.1	0.0	2431.1	477.1	527.6	10761.6	4.6	1670.4	6051.9
11C*	590	11C*: ABS, mixed EEE	0.0	0.0	24.3	0.0	5022.4	446.6	239.0	7991.5	0.0	580.0	617.7
12B	757	12B: ABS, mixed EEE	0.0	68.0	6.2	0.0	596.6	453.9	208.0	8994.1	348.8	1133.6	0.0
12B*	669	12B*: ABS, mixed EEE	0.0	46.8	4.8	0.0	0.0	501.9	200.2	7706.0	694.5	1379.2	0.0
12C	635	12C: ABS, mixed EEE	0.0	8.4	23.6	0.0	2546.1	634.8	413.3	11199.7	1035.1	1922.8	0.0
13B	1081	13B: ABS, cable drums ("recycled")	558.4	19.0	14.2	0.0	1448.7	501.9	235.4	2094.3	88.5	1823.8	0.0
14B	925	14B: ABS, HA & AP ("clean")	0.0	6.7	15.5	0.0	784.8	326.5	292.4	1206.5	8.3	765.9	0.0
14C	72	14C: ABS, HA & AP ("clean")	0.0	13.5	22.5	0.0	1398.6	1146.9	295.2	4335.3	762.5	6355.8	0.0
15C (P)	782	15C: ABS, HA & AP ("dirty*)	264.2	0.0	13.6	0.0	1470.5	976.5	1426.6	3454.8	224.3	6399.6	0.0
16B	827	16B: HIPS, CRT TVs	0.0	13.2	9.2	0.0	498.0	250.7	359.8	1251.0	102.7	2620.7	0.0
16C	69	16C: HIPS, CRT TVs	130.6	7.4	55.0	0.0	1746.7	907.4	144.2	1527.3	293.7	7497.1	0.0
17B	679	17B: ABS, printers	0.0	24.1	2.3	0.0	469.4	389.4	93.7	11849.7	142.1	850.1	0.0
17B*	673	17B*: ABS, printers	0.0	24.3	5.8	0.0	885.3	524.6	258.1	10266.2	358.2	1354.3	0.0
17C	208	17C: ABS, printers	0.0	25.0	25.5	0.0	1170.0	819.0	421.4	14105.5	2679.5	4652.6	0.0
18B	835	18B: ABS, CRT monitors	0.0	53.8	33.5	0.0	596.7	346.3	170.2	12399.2	0.0	793.9	0.0
18C	1118	18C: ABS, CRT monitors	0.0	8.1	41.5	0.0	1278.3	316.7	677.7	12180.5	0.0	844.4	4885.0
19B	758	19B: ABS, CRT monitors	0.0	52.6	10.3	0.0	524.7	372.8	320.7	13344.3	0.0	1259.1	0.0
19C	1062	19C: ABS, CRT monitors	0.0	2.8	42.9	0.0	979.2	310.4	434.6	10603.7	0.0	1079.4	3515.8

Sub-sample	Sub-sample weight (g)	Short description	Br mg/kg	Sb mg/kg	Cl mg/kg
05B	1030	5B: ABS, mixed EEE (burn test: "non-FR")	1055.0	465.6	1338.0
05C	55	5C: ABS, mixed EEE (burn test: "non-FR")	13437.0	15488.4	1251.0
06C	1072	6C: FR ABS, mixed EEE (burn test: "FR")	65550.0	32968.2	13144.0
06C*	835	6C*: FR ABS, mixed EEE (burn test: "FR")	38259.0	35197.5	14793.0
07B	332	7B: ABS, CRT monitors (back panel)	1374.0	2157.1	3945.0
07C	1043	7C: ABS, CRT monitors (back panel)	48061.0	35447.5	31352.0
07C*	835	7C*: ABS, CRT monitors (back panel)	46067.0	34099.3	36863.0
08B	1032	8B, ABS, CRT monitors (front panel)	528.0	569.4	749.0
08C	1169	8C: ABS, CRT monitors (front panel)	68280.0	31550.9	11583.0
09B	984	9B, ABS, HA & AP ("clean")	350.0	374.2	1996.0
09C	130	9C, ABS, HA & AP ("clean")	2053.0	2178.8	4698.0
10C (P)	742	10C: ABS, HA & AP ("dirty*)	1283.0	1072.6	7841.0
11B	586	11B: ABS, mixed EEE	265.0	588.7	518.0
11C	834	11C: ABS, mixed EEE	30123.0	28561.3	6192.0
11C*	590	11C*: ABS, mixed EEE	37944.0	23022.6	5087.0
12B	757	12B: ABS, mixed EEE	678.0	1035.4	1091.0
12B*	669	12B*: ABS, mixed EEE	514.0	304.1	1095.0
12C	635	12C: ABS, mixed EEE	28070.0	17719.5	7948.0
13B	1081	13B: ABS, cable drums ("recycled")	1347.0	1174.8	1283.0
14B	925	14B: ABS, HA & AP ("clean")	190.0	93.3	1972.0
14C	72	14C: ABS, HA & AP ("clean")	1805.0	993.8	1667.0
15C (P)	782	15C: ABS, HA & AP ("dirty*)	9698.0	4006.1	8103.0
16B	827	16B: HIPS, CRT TVs	361.0	263.6	1033.0
16C	69	16C: HIPS, CRT TVs	27783.0	16189.6	3567.0
17B	679	17B: ABS, printers	66.0	96.0	889.0
17B*	673	17B*: ABS, printers	54.0	0.0	869.0
17C	208	17C: ABS, printers	1612.0	2053.5	1426.0
18B	835	18B: ABS, CRT monitors	437.0	1286.2	1503.0
18C	1118	18C: ABS, CRT monitors	60870.0	35343.8	18543.0
19B	758	19B: ABS, CRT monitors	355.0	335.5	1037.0
19C	1062	19C: ABS, CRT monitors	40245.0	33570.3	11549.0