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Small WEEE: Determining recyclables and hazardous substances in plastics

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ABSTRACT

An examination regarding the determination of recyclables and hazardous substances in small waste electrical and electronic equipment (WEEE) found in the residual household waste stream of the city of Dresden, Germany, is described. Firstly, attitudes towards the disposal of small WEEE in the latter are assessed, and product types and categories which mostly contribute to its composition are identified. Physical parameters which could be used as mechanical sorting criteria are measured, and the material composition of the small WEEE found is determined. The hazardous substances' "base" charge in the residual waste is established by means of atomic absorption spectrometry and ionic chromatography, as a first step in estimating the contribution of small WEEE to its pollutant load. Consequently, the content of small WEEE plastics in key heavy metals and halogens is determined. Key conclusions are drawn concerning the future strategic development and practical implementation of the 2002/96/EC Directive, in relation to small WEEE management and recycling.

1. Introduction

Waste electrical and electronic equipment (WEEE) has been identified as a priority waste stream by the European Union (EU) and receives increasing attention as it constitutes in the EU15 states the fastest growing waste stream, with a growth rate almost three times higher than that of average municipal solid waste (MSW, 3–5% annually) [1]. In response, the European Commission adopted the 2002/96/EC "Directive on Waste Electrical and Electronic Equipment" [2] (hereafter WEEE Directive). It provides, amongst others, that WEEE should be collected separately in all member states, sets the target of a 4-kg per capita per annum mandatory separate collection quota, and defines recovery and component, material and substance reuse and recycling rates for 10 WEEE categories.

Furthermore, according to the 2002/95/EC "Directive on the restriction of the use of certain hazardous substances in electrical and electronic equipment" [3] (hereafter RoHS Directive) and its amendments, EU member states have to ensure that all new electric and electronic devices do not contain the heavy metals Hg, Cd, Pb, Cr(VI) and the brominated substances PBBs and PBDEs over certain maximum concentration values. This restriction is in effect since 1 July 2006.

Problems associated with WEEE have been acknowledged relatively recently and the focus has been on the disposal of large items, or those small items with a high residual value. Even though white goods (a term referring to "large household appliances", e.g. fridges, washing machines) make up the majority by weight, small and medium sized items constitute the vast majority by number. A variety of appliances are discarded by consumers, often in different ways depending on size, with small WEEE (hereafter sWEEE) being easier to dispose of than larger ones. The term small WEEE refers to electrical and electronic equipment (EEE) that due to their small size and weight are able to be disposed of in the general household refuse, and are also referred to as "bin-suitable". Small WEEE includes EEE from almost all WEEE Directive Annex I B categories, with the exception of "large household appliances" and "automatic dispensers". Main examples are "small household appliances" (e.g. toasters, shavers), "information technology & telecommunications equipment" (e.g. telephones, mobile phones, calculators), "consumer equipment" (e.g. radios, speakers), and "toys, leisure & sports equipment" (e.g. videogame consoles).

The majority of sWEEE pose a number of unique problems for reuse and recycling due to their size and diversity and it is important that mechanisms are put in place to ensure they are not overlooked: small size means that they are easy to dispose of in general refuse, such items do not pose any difficulties as, for example, a washing machine might do due to size and weight; the infrastructure in place that separately collects sWEEE is inadequate and there is significant lack of expertise related to its collection and treatment; a wide spectrum exists regarding product types, item weight and size; many have been produced as 'not intended to be durable' items, and hence without upgradeability and reuse in

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mind; the variety, complexity and cost of sWEEE, along with low market demand, frequently makes reuse and recycling unviable; small, “bin-suited” WEEE is perceived as a waste fraction that is heterogeneous, compact and difficult to dismantle [4,5].

Thus, it is important to look at the issue specifically in relation to small items since, even if many countries can rather easily meet the WEEE Directive targets by current systems dealing with large appliances, it is expected that all WEEE types must be coped with [4]. The WEEE Directive sets on the one hand not only an overall separate collection rate, but also concurrently recovery, and reuse and recycling quotas ranging from 70 to 75% and 50 to 65%, respectively, for the WEEE categories encompassing sWEEE.

The collection system in Germany has not been entirely successful in convincing consumers to hand in their used appliances through dedicated channels. Consumers persist in the habit of discharging sWEEE into the refuse bin as regular household waste. In spite of the obligation for its separate collection, sorting analyses reveal that sWEEE constitutes up to 1.5% (w/w) of the household residual waste total mass [5–7]. Hence, significant quantities are expected to be found in this waste stream in the present and in the future, bringing current collection schemes into question.

There is limited information regarding components and recyclables that constitute sWEEE, as well as its potential content in hazardous substances and preparations—information vital for plants active in recovery and recycling of this waste fraction, as reported by e.g. [5,8–10]. Information on the characterization of the actual chemical composition and contents of specific pollutants in sWEEE is scant and limited to a small number of studies [8,10–14], which mainly rely on samples taken from the output streams of WEEE recycling units. It is also reported that sWEEE contributes highly to the pollutant load of residual MSW concerning elements such as Cd, Pb and Br as alleged in [15], whereas its introduction into waste incinerators results in high concentrations of heavy metals in the slag, the flue gas or the filter cake [16]. Thus, it is important to look at the sWEEE issue on close examination just as for avoidance of several environmental contaminants entering various disposal routes, entailing adverse effects to the environment and human health. Besides, the efficiency of manual or mechanical separation has on the one hand been addressed by several authors [17–21], yet there still remains limited information on its separation efficiency as regards hazardous substances in sWEEE components [8].

Modelling requirements for sWEEE/residual waste separation technologies is thus needed for a number of reasons. Moreover, sWEEE composition can change significantly due to legislative provisions and technical, economic and/or social developments. Hence, chemical analysis presents a useful means of determining changes in composition and assessing the usefulness of legislative, organizational and technical measures. For the purpose of this study, focus was given on elements with imposed RoHS restrictions, a higher environmental relevance and suspected abundance, namely heavy metals Pb, Cd, Hg, Cr(VI), Cu, Zn, and Ni, and halogens Cl and Br, and not on elements such as Pt or Au which however provide the recycled item with a higher residual value and remain important from an eco-efficiency and recycling aspect.

Several issues arise concerning the future management of small WEEE: how and why it should be successfully diverted from the MSW stream; the reuse potential for these appliances and the most efficient strategies for meeting the recovery targets of the WEEE Directive; the product types that require selective treatment; the influence of the RoHS Directive on future sWEEE composition. It is believed that this work is of unique importance not only due to knowledge shortage on all issues previously addressed, but also due to the combinative methodology used. It aims at depicting some of the challenges facing sWEEE management and contributing to the minimization or elimination of related problems; tackling the sWEEE issue is just one, albeit important, step towards environmentally sustainable waste and resource management.

2. Experimental

2.1. Samples

The manual separation of sWEEE from residual MSW in specific areas of Dresden, Germany, namely the boroughs Gorbitz, Dölszchen, and Striesen, took place during the second half of 2006. They were selected on the basis of sample taking from different parts of the city, representative of its different housing and social characteristics. These differences are being roughly characterized by the “land development structure” index (German term: Bebauungsstruktur) of each area. This index can be assigned a lowest possible value of 1 and a highest possible of 5. Table 1 also depicts the population of these boroughs (the city has in total *ca.* 510,000 inhabitants).

Approximately 5 tons of MSW from each region were examined for their sWEEE content. This amount was considered to be the best compromise between the effort required by the laboratory workforce and the need to separate significant MSW quantities. Samples were taken from the refuse collection vehicle (RCV). *Ca.* 180 kg of sWEEE and single parts were separated in total, and 5.6 kg of batteries. The fractions obtained from the sorting analyses were ultimately MSW with grain size >10 mm, MSW < 10 mm, batteries and sWEEE.

2.2. Sample processing

All sWEEE appliances were dismantled by means of simple tools, e.g. screwdriver, pliers, to the extent possible without exercising excessive force. Solidly built components, such as transformers or printed wiring boards (PWBs) were not disassembled. Materials were divided by visual identification or permanent magnets into the following fractions: ferrous and non-ferrous metals; plastics; rubber; electronic components like PWBs and liquid crystal displays (LCDs); electric and other electronic components (capacitors, speakers, etc.); batteries; cables; not possible to be disassembled materials (hereafter “bonded”); others (glass, textile, paper, wood). A laboratory precision balance was used. For detecting the various polymer types which constitute the sWEEE sample, the near-infrared spectroscopy (NIR) Unisort P system (RTT Systemtechnik, Zittau, Germany) was chosen.

Prior to chemical analyses, MSW and sWEEE plastic samples were cut into pieces, dried and ground into grains less than 1 mm in size using a cutting mill (SM 2000, Retsch, Göttingen, Germany). For quantification of the MSW pollutant load (sWEEE and other metals excluded), microwave digestion was selected, followed by analysis

Table 1
“Land development structure” index for the selected areas and characteristics

Borough	Index		Population
Gorbitz	5	High multistoried buildings, high population density, joint waste bin use (660, 770 or 1100 l)	~21,000
Dölszchen	1	Detached houses, small settlements, “individual” waste bin use (≤240 l)	~34,000
Striesen	3	Semi-detached or small apartment buildings, usually suburbs, “individual” waste bin use (≤240 l)	~9,000

Table 2
Results of the sorting analyses, conducted during the 2nd half of 2006 (kg and % (w/w) composition)

Borough	MSW >10 mm		MSW <10 mm		sWEEE		Batteries	
	kg	%, w/w	kg	%, w/w	kg	%, w/w	kg	%, w/w
Gorbitz	4926.8	96.22	141.7	2.77	49.84	0.97	2.1	0.04
Dölszchen	4263.8	94.46	163.9	3.63	84.45	1.87	1.8	0.04
Striesen	4176.4	92.48	292.1	6.47	45.6	1.01	1.7	0.04
Total	13367.0	94.46	597.7	4.22	179.89	1.27	5.6	0.04

with flame, hydride generation or graphite furnace atomic absorption spectrometry (AAS) for the determination of heavy metals (Hg, Pb, Cd, Cu, Zn, Ni). A PerkinElmer model 4100 flame AAS and a 4100 ZL graphite furnace AAS were used (Bodenseewerk PerkinElmer, Überlingen, Germany). To determine halogen levels (Cl, Br), oxygen bomb combustion was chosen, followed by ion exchange chromatography (IEC), according to DIN [22]. Analyses were carried out with an ion chromatograph 733 IC Separation Center, equipped with a 709 IC pump, a thermostatted 732 IC conductivity detector, a 750 Autosampler and continuously regenerable suppressor (all Metrohm, Herisau, Switzerland). Regarding sWEEE plastics, the same instrumentation and procedures were applied to determine the levels of Pb, Cd, total Cr and the halogens. Preceding analyses were carried out for elements of atomic number >13 by means of portable XRF (Niton XLt, Billerica, MA, USA) with no sample preparation.

3. Results

3.1. WEEE in household waste

Findings of the waste sorting analyses are summarized in Table 2. It is noted that the sWEEE content was considerably higher in the least densely populated region (Dölzschen). Furthermore, based on an average of 1.27% (w/w), the annual generation of sWEEE in MSW per capita amounts to 2.52 kg year^{-1} inhabitant^{-1} and the absolute amount disposed of in MSW was 208 × 10^{6} kg year^{-1}. (It is assumed that, for 2005, approximately 199,500 kg inhabitant^{-1} of household residual waste were collected in Germany.) In contrast, previous publications report of lower values [5–7], revealing an increasing trend. This suggests that the German market is not fully saturated, whilst technological advancement, particularly in the information and telecommunications (ICT) sector, results in frequent and easier equipment replacement. Based on the same sources, as regards batteries and accumulators, it can be concluded that disposal in MSW is declining as a result of more effective separate collection schemes. Yet it is estimated that the former still remains the main disposal route [7].

3.2. WEEE categorization

All sWEEE found in the MSW were categorized according to Annex I B of the WEEE directive per electrical and electronic equipment (EEE) category. A wide range of different types was covered and appliances of all categories were included. Even for categories 1 and 10 a small number of devices were found, in spite of the fact that, for these categories, the majority of products are too big to be discarded in the ordinary refuse bin. Detached components, single parts and products which could not be categorized elsewhere were classified as “category 11”. This concerns mainly luminaries in households, frames, cables, car electronics, etc. It must be noted that results obtained (Table 3) are presented at the level of WEEE categories as defined by EU legislation only and not on the basis of individual devices, for only a small number of each appliance type (e.g. mobile phones, toasters, etc.) was found.

The above reveals that composition of the sWEEE found in the MSW differs between the areas of Dresden. However, it is clear that small household appliances and consumer electronics (CE) “dominate” the sample mass, whilst ICT equipment varies between 3.3 and 5.3% (w/w). Toys and tools were also found in considerable quantities. It is noted that heavy products can substantially influence the total weight of a category. For example, in Gorbitz, 30% by weight of category 2 is occupied by a vacuum cleaner and 48% (w/w) of CE by a single radio set. Moreover, a large part of the sample mass comprises equipment not included in the Directive. Its share is nearly 50% (w/w) and varies between 33 and 59% (w/w). Its presence could be due to compression of the sWEEE in the RCV and/or disposal as single parts. Lastly, comparison with literature findings allows the conclusion that the composition of sWEEE from MSW was generally different in the past, while the share of ICT rises with each passing year [5–7].

Table 3
sWEEE sample composition per category

EEE Category	Gorbitz			Dölzschen			Striesen			Total		
	n	Weight (kg)	%, w/w	*n*	Weight (kg)	%, w/w	*n*	Weight (kg)	%, w/w	*n*	Weight (kg)	%, w/w
1	–	–	–	5	6.05	7.17	–	–	–	5	6.05	3.36
2	14	17.07	34.26	16	9.47	11.21	17	11.58	25.40	47	38.12	21.19
3	3	1.65	3.32	8	4.46	5.28	8	1.97	4.31	19	8.08	4.49
4	3	7.10	14.25	6	6.80	8.06	8	9.28	20.35	17	23.18	12.89
5	1	0.06	0.12	2	0.09	0.11	3	1.51	3.31	6	1.66	0.92
6	–	0.00	–	3	4.68	5.54	2	0.21	0.46	5	4.89	2.72
7	1	0.19	0.38	3	0.51	0.60	5	2.56	5.62	9	3.26	1.81
8	–	–	–	1	2.64	3.13	–	–	–	1	2.64	1.47
9	–	–	–	1	0.24	0.28	–	–	–	1	0.24	0.13
10	–	–	–	–	–	–	1	3.38	7.40	1	3.38	1.88
11	–	23.76	47.67	–	49.51	58.62	–	16.20	33.15	–	88.38	49.13
Total	22	49.84	100	45	84.45	100	44	45.60	100	111	179.89	100

n = number of appliances.

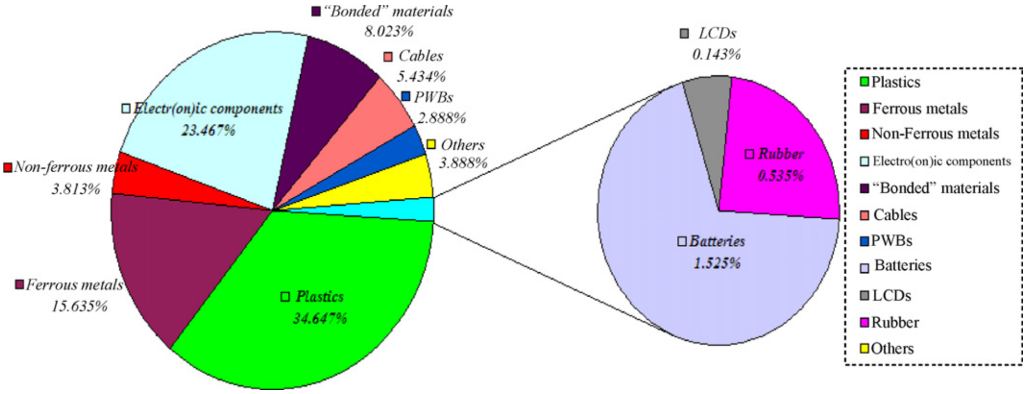

Fig. 1. Material composition of the sWEEE samples (%, w/w).

Table 4
Material composition for each category of the sWEEE samples (%, w/w)

Material fraction	EEE Category										
	1	2	3	4	5	6	7	8	9	10	"11"
Ferrous metals	51.60	8.99	25.27	12.04	10.40	13.32	2.50	7.42	0.27	–	27.92
Non-ferrous metals	2.89	8.22	0.09	1.08	–	2.69	0.23	8.12	–	–	0.70
Plastics	9.85	40.70	27.49	28.17	24.19	9.18	83.60	29.27	76.62	69.48	34.26
Rubber	0.05	0.69	0.79	0.54	–	0.21	1.12	3.25	0.22	–	0.43
Cables	3.00	7.55	3.34	2.80	0.77	7.02	2.26	–	0.46	8.50	6.54
PWBs	0.08	0.52	10.17	6.77	–	0.92	3.84	–	22.44	4.33	0.72
Electr(on)ic components	28.16	18.41	4.45	38.48	64.64	66.11	3.92	20.09	–	1.48	13.78
"Bonded" materials	4.35	11.77	11.09	5.28	–	0.53	0.004	–	–	15.32	7.29
Various	–	2.53	14.03	3.00	–	0.04	1.91	31.84	–	–	3.33
Batteries	–	0.49	2.63	1.74	–	–	0.53	–	–	0.33	5.04
LCDs	–	0.12	0.64	0.08	–	–	0.09	–	–	0.56	–

3.3. WEEE characteristics

The sWEEE sample was characterized while bearing in mind a range of parameters which portray its reuse potential (condition, level of damage, age) or which could be used as criteria for developing automated separation processes (weight, volume, projection surface). Findings indicate (data not shown) that reuse of whole appliances or components is not possible. A large proportion of the sample (*ca.* 52%) consists of equipment which is all but destroyed. It is also believed that due to the effects of dirt and age, there is low reuse potential, even for equipment with a high residual value which had been slightly damaged. Moreover, parameters like weight, volume, and projection surface vary over a very wide spectrum (data not shown). For example, weight ranges between 0.17 and 5.35 kg and its average value is approximately 832 g. It is also difficult to identify all these parameters through separation processes due to dirtiness and damage caused within the MSW. Thus, they cannot be used as criteria for the separation of sWEEE from the heterogeneous residual household waste stream. The probability of finding similar parameters for this purpose also seems low [23].

3.4. WEEE composition

Fig. 1 and Table 4 present the composition of the sWEEE retrieved from the MSW stream. The biggest materials fraction makes up the various polymers, corresponding to more than one-third of the sample mass. Electr(on)ic components make up a quarter of it, while ferrous metals content is also very signifi-

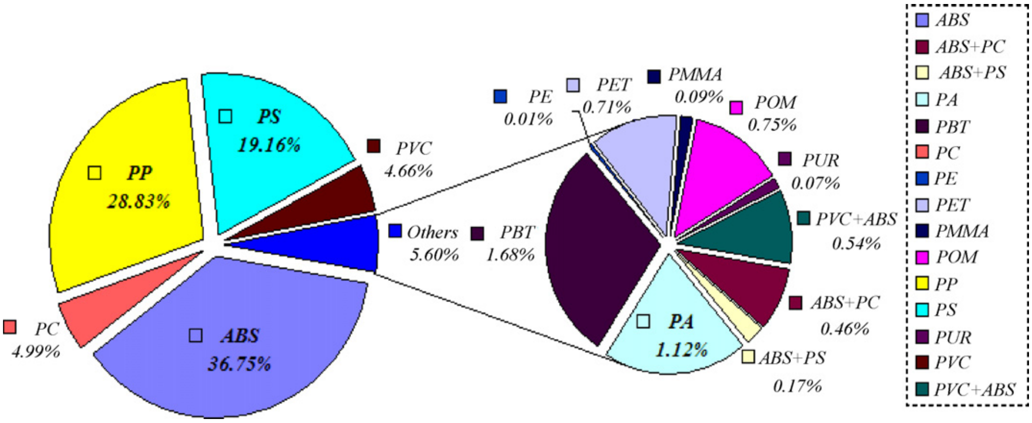

Fig. 2. Polymer types composing the identified sWEEE plastic samples (%, w/w).

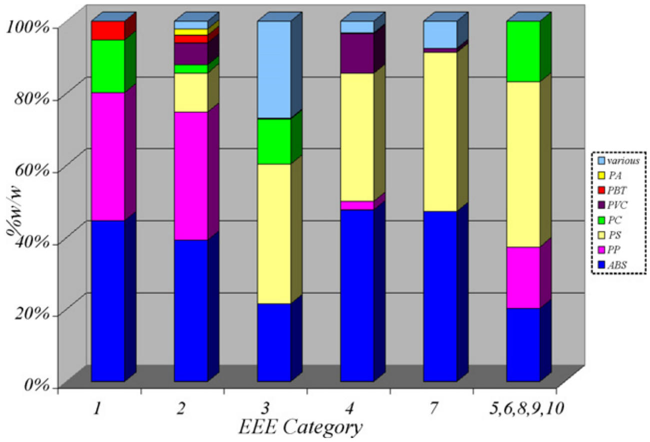

Fig. 3. sWEEE plastic composition per EEE category (%, w/w).

cant. PWBs, non-ferrous metals, "bonded" materials and cables are encountered in small, though important, amounts. Other material fractions like batteries, rubber etc. constitute only a small proportion of the sample mass. Plastics dominate categories 2 and 7, while for the rest (excluding categories 5 and 8–10, for which the sample of dismantled appliances is not representative) their share is relatively consistent (25–30%, w/w), with the exception of category 1, where ferrous metals are by far the largest material fraction. The high percentage of electric (mainly) and electronic components in categories 6, 4 and 1 is noted, while "bonded" materials were primarily encountered in equipment categories 2 and 3. PWBs are found mainly in ICT products as expected. Non-ferrous metals varied between 0.2 and 2.9% (w/w), whereas their higher share in small household appliances contributed substantially to the total average of 3.8% (w/w). It is lastly noted that two products of category "11" were included in the calculations due to their frequency and environmental relevance—luminaries in households and switches.

3.5. WEEE composition—plastics

Only 6.8% (w/w) of the sWEEE plastics bore a moulding mark with regard to the polymer type used. In 87% of cases, marking was confirmed by NIR. Almost half of the plastics were black, ruling out their potential identification; household appliances and toys in particular consisted of light coloured, identifiable polymers. However, ICT and consumer equipment was comprised mainly of dark plastics (82.0 and 93.9%, w/w, respectively)—considerably reducing separation and subsequent recycling options. Nevertheless, 15 different types were identified by NIR (Fig. 2). ABS is the largest fraction, followed by PP and PS. PC and PVC constitute *ca.* 5% (w/w) each. Other polymers are found in percentages ranging from 0.01 (PE) to 1.68% (w/w) (PBT). There is a greater presence of ABS in small household appliances and consumer equipment (Fig. 3). PP constitutes one of the main plastics in categories 1 and 2. On the other hand, PS is almost absent in these categories, but dominates ICT. EEE plastics composition for categories 5, 6 and 8–10 is depicted in one single column altogether as the number of identifiable plastics' samples for each individual of these categories was very low, and would thus be unrepresentative. It is also considered that WEEE composition defines the recycling method to be applied in order for the reuse, recycling and recovery targets of the Directive's article 7 to be fulfilled. In any case, plastics must be taken into account, for they constitute the largest material fraction. A high detection rate of NIR-identifiable polymers facilitates their quantitative mechanical recycling. A low detection rate would lead to failure in accomplishing these targets.

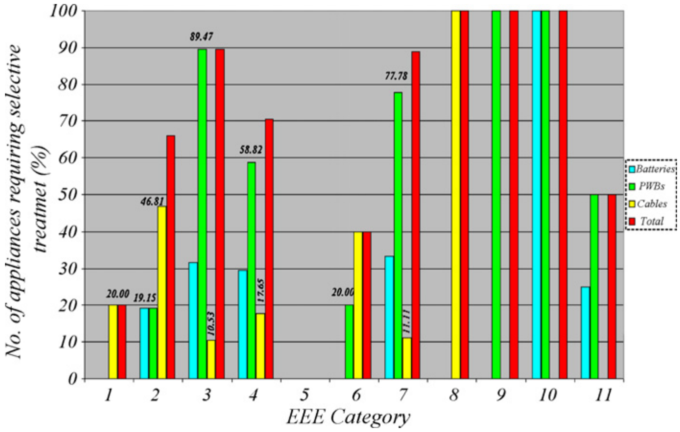

Fig. 4. Frequency of appliances of the sWEEE sample fulfilling at least one criterion for selective treatment (% of total number).

3.6. WEEE selective treatment

According to article 6 of the WEEE Directive, treatment of WEEE must, as a minimum, include removal of all fluids and selective treatment of certain materials and components in accordance with its Annex II. The following relevant criteria were studied, as regards the presence of: batteries and accumulators; PWBs of mobile phones and of other devices if its surface area is greater than 10 cm^2; external electric cables; LCDs of surface area greater than 100 cm^2. Results show that 66.1% of the number of appliances of the sample (76 out of 115) requires selective treatment, for they fulfill at least one of the aforementioned criteria. The largest percentage is encountered for ICT equipment and toys, where the removal of one or more restricted components is necessitated for almost all appliances. There is also an obligation to apply selective treatment to the majority of small household appliances and consumer equipment (Fig. 4). None of the LCDs found had a surface area greater than 100 cm^2. Note also that cables may have been cut off during transportation in the RCV, leading to their classification in category "11".

3.7. Heavy metals and halogens content

Portable XRF (HXRF) analyses focused on RoHS restricted elements. Owing to the large number of samples analyzed (161) it is believed that findings provide an overview of the range and concentration of additives in sWEEE plastics. A very small percentage of samples contained total amounts of Br or Cr, Cd and Pb in concentrations greater than the RoHS limit (Fig. 5). These results should be however used with caution, since they cannot be used for drawing conclusions as regards PBBs, PBDEs or Cr(VI). Results demonstrate that about half of the plastics contained brominated flame retardants (BFRs), while in the majority of the cases Sb_2O_3 was used as a synergist. Moreover, the mass fraction of a single additive in sWEEE plastics can vary over a very wide range. Most elements were found in concentrations below 0.1% (w/w), but concentrations of Br, Sb, Zn, Cu, Fe, and Ti reach or even exceed 10% (w/w). The mean Br content exceeds the level of all other elements and amounts to 0.53% (w/w) of all samples. Analyses with AAS showed that category 3 is the most contaminated with Cr, followed by toys and small household appliances. Regarding Pb and Cd, plastics of CE, small household appliances and ICT products contain them to a greater extent. Thus, most additives were applied in plastics of EEE categories 2 and 4, next to ICT products and toys (data not shown).

Nevertheless, AAS found no element in concentrations above the RoHS threshold values for homogeneous materials in any of the

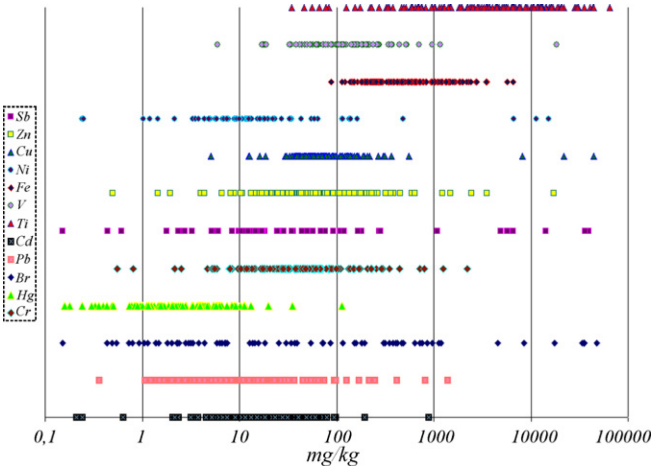

Fig. 5. Concentration range for important elements found in the sWEEE plastic samples.

plastic samples analyzed. It appears that enactment of the RoHS Directive has prompted producers to respond to its demands before they were rendered compulsory. More than 80% of appliances are 1–5 years old, that is, they were produced before its restrictions were set into force.

4. Discussion

Table 5 shows that the MSW base pollutant load lies within an anticipated range, while measurement reproducibility remained within the spectrum expected for analysis of this inhomogeneous waste stream (see for example [8,15]). Moreover, calculated sWEEE (plastics) contribution is very important mainly for Cd, Br and Ni. It should be considered that, in the calculation of their contribution, batteries found in the sWEEE as well as all other material fractions like PWBs were not included. This assumption may considerably lower sWEEE contribution to the MSW pollutant load and subsequently the metals' fraction potentially entering landfills [8,9]. The above unavoidably lead to the question whether the amounts present of these pollutants reflect a significant probable risk.

A further observation is that HXRF constantly overestimates the concentration of RoHS elements, probably due to its inherent limitations, as reported in [11]. HXRF results should be therefore reviewed carefully, particularly near RoHS threshold levels. This is why they are not used for comparison in Table 5 when AAS data was available. HXRF has however been used for analysis even if it overestimates the concentrations of elements as it has already been characterized as a suitable, reliable screening tool to estimate the concentration of a variety of elements in electr(on)ic components [11,24] to reduce testing time and cost compared with other spectroscopic techniques. It allows "go/not go" decisions to be made efficiently and could reduce the number of samples that need to be submitted for confirmatory analysis.

Table 5
Comparison of the pollutant load of MSW and sWEEE plastics, and % contribution of the former to the load of the latter

Element	Waste stream						% Con.*
	MSW		sWEEE HXRF		sWEEE AAS		
	Mean C (mg/kg)	R.S.D. (%)	Mean C (mg/kg)	R.S.D. (%)	Mean C (mg/kg)	R.S.D. (%)	
Pb	120.86	73.53	33.64	404.89	17.41	73.31	0.064
Cd	0.04	53.67	37.73	235.31	5.71	302.34	38.771
Hg	0.14	122.44	5.27	234.52	–	–	14.309
Cl	4,351.57	41.65	–	–	–	–	–
Br	n.d.	n.d.	5,318.96	356.86	–	–	>99,999
Ni	0.34	43.64	476.76	483.87	–	–	86.150
Zn	1,172.06	157.64	362.17	490.03	–	–	0.137
Cu	99,674,277.25	34.53	565.98	712.03	–	–	–
Cr	–	–	99.97	237.19	8.38	116.50	–

C: concentration, R.S.D.: relative standard deviation (%), n.d.: not detected, Con.: sWEEE plastics contribution to the entire MSW pollutant load (%).

Table 6
Comparison between own results and literature data

Element	Own results		Literature data					
	HXRF	AAS	[8]	[12]	[13]	[14]	[9]	[24]
Pb	34	17.41	1,900	100–2,100	127–165	500–1,000	40–196	–
Cd	38	5.71	160	30–240	115–186	200–2,000	2.3–56	–
Hg	5.3	–	0.31	–	0.3–1.4	–	0.29–15	–
Cl	–	–	8,600	1,900–11,000	6,300–6,400	–	n.d.	–
Br	5,300	–	–	4,300–41,000	4,200–6,800	150–250,000	n.d.	up to 110,000
Ni	480	–	1,300	90–800	299–703	–	19–30	–
Zn	360	–	2,300	620–5,100	361–520	120–5,000	187–269	–
Cu	570	–	18,000	80–105,000	–	–	391–406	–
Cr	100	8.38	900	60–380	34–71	–	–	–
Sb	2,000	–	3,500	2,000–13,000	–	1,000–80,000	–	–
Fe	780	–	11,000	440–3,300	1,483–1,673	–	–	–
Sn	140	–	2,300	60–2,100	139–267	500–3,000	–	–
V	430	–	–	35–900	–	–	–	–
Ti	8,000	–	–	1,500–18,400	4,187–4,767	300–90,000	–	–
As	21	–	–	9–46	up to 10	–	–	–

Concentrations in mg/kg, n.d.: not detected.

Table 6 presents a comparison of results obtained with existing literature for various environmental contaminants in WEEE plastics. As shown, it is difficult to draw conclusions about the exact content of WEEE plastics in various elements. Variations are up to 4000%. This result is not surprising; literature refers to analyses performed before 2001, except for [9]. Besides, own results are in the lower region of the concentrations spectrum, implying a significant tendency to reduce hazardous additives in EEE plastics with the passage of time, mirroring new trends in the production sector [10,25,26]. It should be noted that the values refer to different methodological approaches and are related to samples taken under diverse conditions. Studies [8] and [12–14] display values for samples coming from the exit streams of WEEE recycling units based on analyses performed on samples of a different origin and nature than that of this study. It would be therefore wise that they are dealt with caution.

The main drawback regarding recycling of WEEE polymer fractions is the presence of cadmium, PBDEs and even PBDDs or PBDFs formed during polymer recycling as reported in [27,28] at levels close to or above legislative thresholds, since this impedes distribution of recycled materials in the EU market. Hence, production of recycled materials in compliance with European and national legislation has to take account of the elimination of hazardous substances. This could be addressed by a number of approaches presenting different features, as discussed in [8,10].

5. Conclusions

A methodology for addressing a number of issues pertaining to small WEEE has been described. As shown, sWEEE holds a noteworthy proportion of the MSW bulk, with small household appliances and consumer equipment constituting its most significant fractions. *Ca.* two-third of appliances of the sample require selective treatment, whereas batteries, external cables and PWBs must be removed from a large amount of waste equipment with an average weight less than 850 g. The biggest sWEEE materials fraction makes up the various polymer types, while ABS dominates in this materials fraction. Samples analyzed for their heavy metals and halogens content provide an overview of the range and concentration of additives in sWEEE plastics.Findings can also be valuable for estimating sWEEE disposal patterns in residual MSW for cities presenting comparable features. Dresden is a typical example of a moderately large German city comprising of boroughs with different housing and socioeconomic characteristics. Future work shall hence be directed towards a systematic examination concerning the proportions of sWEEE in MSW, in addition to its material composition and sWEEE plastic content of hazardous substances. Such data would serve to discuss different recycling/disposal scenarios and the risk assessment of potential hazards. Further investigation would also be expedient regarding the influence of contained hazardous substances on WEEE recycling processes, particularly regarding contamination of clean fractions in respective exit streams.

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