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The Challenge of Plastic Management for Waste Electrical and Electric Equipment Recycling in the Global South: A Case Comparison between Europe and Latin America

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Abstract: Countries with emerging legislation on the waste electrical and electric equipment (WEEE), but limited infrastructure, may find in other, more robust, systems the tools to develop adaptable and socioeconomically viable management schemes. Additives found in the plastics in electronic goods, such as brominated flame retardants (BFRs), are components of a safety system, but introduce characteristics that result in their waste being hazardous. Established and emerging regulatory systems need to implement legislation that impacts the management of WEEE, to reduce risks to human health and the environment, while maximising opportunities for resource recovery from widely varying materials. To assess the context of developed and emerging regulatory systems, a baseline study was undertaken of WEEE plastics in Scotland and Uruguay. For the identification of BFRs in plastics, an internationally validated screening methodology using X-ray fluorescence was adopted at different processing operations. It was observed that, using a threshold of 830 mg/kg for Br as a BFR tracer, in Scotland, more than 70% of the plastics would be recyclable, while, in Uruguay, that fraction dropped to 50%. These results, and the wider literature discussion, highlight the impact that regulatory frameworks have on the quality and recyclability of recovered material. We identify future actions to be considered by policy-makers for a more sustainable regulatory approach.

Keywords: waste electrical and electronic equipment (WEEE) plastics; brominated flame retardants (BFRs); X-ray fluorescence (XRF); legislation; Latin America; Europe

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1. Introduction

Article 3 of the European Directive 2012/19/EU [1] defines electrical and electronic equipment (EEE) as equipment that is dependent on electric currents or electromagnetic fields in order to work correctly. The circulation of such currents can lead to the generation of heat, so, depending on how much is generated during operation, it could be necessary to take safety measures to prevent potential fires associated with the presence of combustible materials, such as plastics. To this end, EEE manufacturers must add compounds such as flame retardants (FRs), to prevent this hazard. These FRs can be halogenated or non-halogenated, and their presence is defined according to flammability standards. Among the halogenated FRs are brominated flame retardants (BFRs). Certain BFRs exhibit physicochemical and biological characteristics that have led to their classification as persistent organic pollutants (POPs) by the Stockholm Convention. In addition, there are other BFRs that, despite not having been classified within this group to date, are considered to be hazardous and/or ecotoxic, as is the case of TBBP-A (tetrabromobisphenol A), which is widely used in EEE ([2–4]).

The presence of flame retardants in polymers can be detrimental to the recycling of materials and, thus, inhibit progression towards a circular economy. For example, in the

EU and the UK, according to (EU) Directive 2019/1021 [5] and the POP Regulations [6], respectively, any waste material containing POPs must be treated to ensure that the POPs are destroyed or irreversibly transformed. Certain consumer product waste streams, such as WEEE, contain both POP-contaminated plastics and recyclable plastics, meaning that these fractions must be separated before further recycling, or the total mixture must undergo treatment such as incineration, which prevents any material recovery and increases the carbon footprint of management operations. This highlights the need for technological options that allow efficient and effective separation, to maximize the volumes sent for recycling. However, at present, there are few techno-economically viable processes applicable at industrial scale, with most sorting being based on the "sink and float" method [7,8].

Different techniques have been studied for the characterisation of plastics containing BFRs and Sb_2O_3, a hazardous synergist often found in POP-contaminated plastics. To quantify BFRs, the established methods include gas chromatography with electron capture detection or mass spectrometry, as well as liquid chromatography with different coupled detectors [9–12]. In addition, the method generally used for the determination of Sb_2O_3 is analysis via atomic spectroscopy, such as ICP/OES, after the chemical extraction of Sb from the matrix. As this compound is the only source of Sb in plastics, all the Sb measured is attributed to it.

Technologies based on optical and spectrometric methods, such as hyperspectral imaging (HSI), have also been developed. While the application of HSI is being implemented on the industrial scale [13–15], it requires significant equipment investments that are not easily rationalised, due to the low prices of virgin polymers.

These methods to determine compliance with regulatory limits are technically and economically demanding, and incompatible with the high material throughput required for effective processing at the industrial level. For this reason, during the past decade, research has increasingly focused on more practical alternatives, such as X-ray fluorescence (XRF) as a fast, non-destructive, and effective technique, through which it is possible to rapidly determine total concentrations of Br and Sb as tracers of BFRs and Sb_2O_3, respectively [16,17].

There are no global regulations governing the use of flame retardants in consumer products; thus, different countries impose different standards and restrictions. This variability can result in the use of certain formulations of FRs being permitted in some regions of the world, but restricted in others. The Stockholm Convention centralizes the commitment of 186 countries [18] to regulate the treatment of persistent organic pollutants. However, a high percentage of the countries that have ratified the Convention still do not have the regulations in place to apply its requirements on the national level. On the other hand, in other countries, although the Convention has been ratified, and the corresponding regulations put in place, compliance is not regulated, and consumer products are manufactured without complying with the provisions of the Convention. This creates great complexity for international trade and for the harmonization of safety regulations.

The WEEE waste stream contains various resources, including precious metals (i.e., gold, platinum, copper, silver), as well as other valuable metals, such as iron and aluminium. It is estimated that, currently, 30% of WEEE by weight is plastic material, of which 9% contains BFRs, with only a small fraction corresponding to restricted BFRs, such as octaBDE or decaBDE [19]. Because of the restrictions imposed on their use, the concentrations are decreasing. However, given that EEE is estimated to have a useful life of approximately 12 years, the equipment containing these compounds is only now being disposed of [19]. Furthermore, BFRs are usually used in combination with antimony trioxide, typically found in TV/display equipment in a concentration of approximately 33–55% of the Br content [19–22].

Consequently, WEEE is currently a global challenge, with adequate handling, treatment and disposal being key to its sustainable management [23]. Worldwide, the management of this unique waste stream is very diverse; there are countries where collection systems are well defined, regulated, and implemented, and countries where there is no legislation, control, or management system [24,25].

To evaluate the impact of regulatory, economic, and environmental frameworks on WEEE management, we selected two discrete regulatory domains in Latin America and Europe as case studies. Primary data were collected on the characteristics of the WEEE plastics recovered in both cases. Display equipment was targeted as a category of appliances with a significant BFR content [5,6] and a higher penetration in Latin American markets [26]. Being a comparable component stream of WEEE in both locations, the objective was to gather compositional data on the plastic components. By using reproducible and validated characterisation, a good primary dataset could be used as a baseline to allow a comparison of the impact of the national and global legal framework on the characteristics of the materials reaching the WEEE stream. This would also help to identify the regulatory gaps that put Global South countries at a disadvantage in terms of hazardous waste management. Additionally, it considers the validity of the current regulations, while providing evidence for policy-makers to support the development of new guidelines. It supports the adaption of the available infrastructure and technology, and validates the potential of different management options.

2. Case Study

In Latin America, the project "Strengthening national initiatives and improving regional cooperation for the environmentally sound management of POPs in electronic and electrical equipment waste" (PREAL), implemented by the United Nations Industrial Development Organization (UNIDO), has been underway since 2017 [27]. This project brings together 13 countries in South America, providing technical, legislative, and management advice and financial support for the development of activities. One of the main objectives of this initiative is to strengthen WEEE management policies at the local and regional level for the protection of the environment via the appropriate management of hazardous waste and the recovery of valuable raw materials.

In 2022, scientists representing PREAL countries were invited to share research advances in the framework of the E-Waste Academy Scientist Edition (EWAS) organized by UNIDO, in which the corresponding author of this article participated. In this instance, it was identified that, even though, as part of PREAL, the countries involved had the opportunity to select technology for the characterization of WEEE with respect to POP content, Uruguay was the only country that did not choose h-XRF technology. Thus, the opportunity was identified to collaborate with the Ministry of Environment of Uruguay through the study of a particular stream of WEEE, by applying a validated method of Br and Sb analysis via h-XRF as a starting point for the characterization of these wastes. The results of this study not only provide detailed knowledge on the composition of the waste stream, but also allow an evaluation of the suitability of the technology to be applied at scale.

Another challenge that Uruguay presents at the time of this study is the lack of specific legislation on WEEE and POPs. Consequently, it was also considered that this study would analyse the regulatory framework, and contrast it with a comparable country in terms of population and geography, where the regulation is more developed and effectively implemented.

Europe has led technological and regulatory development worldwide, and the frameworks that are consequently established provide a good reference base. The initial phase of our work was to assess the state of the art for the application of h-XRF for the determination of Br/Sb in WEEE plastics from the EU regulatory region (and included the UK and its devolved administrations). Subsequently, the demographic characteristics were considered, with the closest match to Uruguay (19 inh/km^2) being Scotland (70 inh/km^2). It should be noted that there are important socioeconomic differences resulting from the progress of economic development between Europe and the Global South. The selection of Scotland (rather than the UK) was feasible, as this devolved region has regulatory responsibility for environment, education, health, and economic development and, whilst linked to systems across the UK, has independent responsibility for waste management.

3. Materials and Methods

3.1. Samples for Primary Characterization

In Uruguay, the samples were obtained from a WEEE management company specialized in the treatment of diverse waste including non-ferrous metals recovered from different streams (e.g., electric motors, pipes, electric cables, car catalytic converters, electronic scrap, and other waste), batteries and WEEEs including CRT monitors, personal computers, cell phones, home appliances, servers, peripherals, and microprocessors, among others (Company 1).

In Scotland, the samples were taken from a display equipment recycling plant (Company 2). Focusing on display equipment, this is one of the UK's leading recycling companies, and has successfully developed a validated methodology for the identification and sorting of TV plastic housing according to its Br/Sb contents as tracers of POPs and hazardous compounds, respectively [8,10].

In both companies, the back housing of the equipment was retrieved whole via manual dismantling, from which one sample of 6 cm in diameter was cut, for h-XRF analysis. A total of 80 samples were collected, comprising mainly black plastic. Relevant information on the equipment sampled from both companies is presented in Table 1.

Table 1. Relevant information on the equipment sampled from Company 1 and 2.

Sampled Equipment Characteristics	Company 1 (Uruguay)	Company 2 (Scotland)
Year of recovery	The equipment sampled was received from different Uruguayan companies for replacement, either due to changes in technology or breakage over 2 years (between 2021 and 2022), comprising LED TVs and small display equipment (i.e., tablets).	The equipment sampled was received from different UK Compliance Schemes and UK Councils, from both households and non-household sources. All the equipment was received on site during the year 2022, comprising LED and LCD TVs and monitors.
Year of manufacture	2007–2014	2007–2022
Origin	China and Mexico	China, Czech Republic, Poland, Turkey, United Kingdom

3.2. Statistical Significance of Selected Sample Size

In Uruguay, the sample size was defined considering that 5.6 kt of display equipment waste was generated, and assuming that the previously mentioned 0.11 ton of plastic recovered from WEEE came from display equipment. Therefore, considering that an average weight of 0.6 kg per plastic casing results in 275 items recovered, with a confidence level of 95%, a sample size of 80 items yields a margin of error lower than 10%. As for Scotland, considering an average weight of display equipment of 13 kg and 164 kt of plastic recovered results in 27,000 units. Thus, for the same confidence level (95%), a sample size of 80 items has an associated margin of error slightly over 10%, which is deemed acceptable for the purpose of the present study.

Regarding the differences in manufacture years between samples collected in both countries, it must be considered that there are limitations associated with the socioeconomic levels and WEEE collection infrastructure. On one hand, in Uruguay, changes in technology are delayed with respect to Scotland, so that, although the sampling was carried out during the same period, the samples recovered in Uruguay date back to the year 2014 while, in Scotland, some items recovered were manufactured in the sampling year. On the other hand, given that, in Uruguay, there is no established system for the collection of WEEE, the items recovered correspond to those collected from public or private organizations, which biases the sample to items generally similar and from the same year of manufacture, because they were acquired at the same time. This is not observed in Scotland, as the items recovered are not only from organizations, but also from households.

3.3. Sample Characterisation

Br and Sb were targeted as tracers of brominated flame retardants. The concentrations of these elements in each sample were determined using the VANTA^{TM} X-ray Fluorescence Analyser—C series, with a rhodium (Rh) anode tube, using the RoHS method. All samples were analysed using the facilities of Company 2.

Each analysis was carried out in triplicate for consistency, with the window of the analyser placed directly on the surface of the sample without changing its position in between replications. A detailed description of the methodology and quality control/quality assurance used for plastics characterization is included in [28].

3.4. Classification Criteria

To classify items as POP/non-POP, the criteria presented in Table 2 was followed, based on Br and Sb concentrations. These criteria were set under the most conservative approach, considering that all detected Br is present as decaBDE, with a concentration limit of 1000 ppm of this compound, to classify an item as POP waste. This limit was based on those defined in EU Directive 2019/1021 at the time of the study, and it corresponds to a Br concentration of 830 mg/kg.

Table 2. The sorting categories, as defined in the database according to the total Br and Sb concentrations.

		Bromine (Br) Concentration [mg/kg]	
		<830	≥830
Antimony (Sb) concentration [mg/kg]	<8300	Recycle	POP waste
	≥8300	Hazardous waste	POP and hazardous waste (POP and HAZ)

Additionally based on EU regulations, the concentration limit for Sb was based on the Chemical Classification, Labelling and Packaging regulation (EC No 1272/2008), which establishes a concentration limit of Sb_2O_3 of 10,000 mg/kg to classify any waste as hazardous. This corresponds to an Sb concentration of 8300 mg/kg.

3.5. Literature Review

A review of the literature and legislation, based on Cronin et al. [29], was carried out.

3.5.1. WEEE Scenario

Uruguay is a South American country with 3.3 million inhabitants unevenly distributed over 176,215 km^2, with over half of the population centred in its capital, Montevideo [30]. With a current GDP per capita of USD 17,313 [31], the economic growth of Uruguay has fluctuated in the last two decades, with a marked decrease in 2020 as a result of the global pandemic. According to the latest reports, in 2019, the rate of domestic WEEE generated was 12 kg per inhabitant (kg/inh), from which only about 4% was formally collected, including 3.2 kg/inh of plastics [32]. It is expected that these numbers have not changed significantly to date, as both the economic and waste management infrastructure have remained relatively unchanged. It is important to mention that the volumes of WEEE produced in Uruguay was not quantified directly, but calculated using a globally accepted methodology defined by UNU (United Nations University), based on the volumes of EEE placed on the market and the average service life of each equipment category [33].

Scotland has a population of 5.5 million inhabitants [34] in an area covering 77.933 km^2, and a GDP per capita of USD 45,251 [35], with the amount of domestic WEEE generated in 2019 considerably lower than that of Uruguay, at 6 kg per inhabitant [36].

Table 3 presents the data for the different categories of WEEE generated for both Uruguay and Scotland.

Table 3. The WEEE generated in 2019 by category (Uruguay and Scotland). Source: [33,36].

Category	Uruguay (Ton/Year)	Scotland (Ton/Year)	Difference
Monitors, screens, and display devices	5613	3563	Uruguay 36%
Large appliances	7016	9421	Scotland 26%
Small appliances (includes small computer and telecommunications equipment)	14,987	12,691	Uruguay 15%
Temperature exchange equipment (including fridges and freezers)	9313	7233	Uruguay 22%
Fluorescent tubes and other light bulbs	677	151.6	Uruguay 78%

In Uruguay, an increase in consumption has been observed, which leads to an increase in the WEEE generated, due to the calculation method used. Likewise, EEE are subjected to rapid technological changes, programmed obsolescence, and short lifespans, as observed globally, also recognising the rather low availability of repair options. It is also relevant to mention that the majority of recovery sources are mainly from the business sector, rather than households, according to the Ministry of Environment [33].

As in most Latin American countries, due to the socioeconomic conditions, the disposal of EEE is buffered, as there is a tendency to store unused equipment at home, or to give it to others who perceive a value from it for reuse. It is common that, once the decision to discard is made, informal systems are chosen, because either there is no formal management structure available, or the user is not aware of the options available to them. In addition, informal managers generally provide financial compensation and door-to-door collection, while formal channels do not.

In a study carried out for the quantification of WEEE in Uruguay [33], it was identified that the categories with the greatest influence on the total volume were small appliances and temperature exchange equipment (including fridges, electrical heaters, and air conditioning appliances, among others). Contrary to what might be expected, monitors, screens and devices with screens, and small computer and telecommunication devices have decreased in the last decade. It is estimated that this may be associated with several factors, such as the decrease in the weight of each individual piece of equipment, or the replacement of technologies such as CRT monitors and televisions by devices with more than one function, such as laptops, tablets, or cell phones. However, it is important to note that the WEEE calculation does not consider the replacement of CRT equipment by monitors and flat screens, which have a considerably lower weight. The amount of CRT equipment disposed of in Uruguay is likely to be higher than that in Scotland, considering the delayed shift in technology in developing countries [33,37].

Looking at the volumes of lamps, the behaviour for Uruguay is as expected, with an upward trend as, in 2013 and 2015, agreements were signed by the central and local governments to promote the replacement of public and private lighting with LED technology ([38,39]).

Regarding temperature exchange equipment, in Scotland, most households, offices, and education centres do not have air conditioning equipment, whereas in Uruguay, due to the very high temperatures in summer, it is a common commodity [40,41]. Additionally, the fridges and freezers disposed of in Uruguay are likely to be older and, therefore, heavier, than those disposed of in Scotland. There is no obvious explanation for the higher volumes of small appliances other than potentially lower quality equipment being placed on the market in Uruguay, resulting in a shorter use–dispose–replace cycle.

Looking at the amount of formally collected WEEE, the low percentage reported for Uruguay is explained by a poor regulatory system and a lack of infrastructure for the proper and formal management of this waste [32]. However, even though Scotland has a well-established regulatory framework, with the WEEE Directive having been in place since 2007, in discussion with SEPA (Scottish Environment Protection Agency), the lack of accurate data on waste generation related to illegal activity was also raised as a concern.

Due to the environmental and public health concerns associated with certain POPs/BFRs, efforts have been made to regulate or phase out their use. For example, Directive 2011/65/EU (RoHS) [42] in the European Union and the United Kingdom restricts the use of certain BFRs, such as polybrominated biphenyls (PBBs) and PBDEs, in electrical and electronic equipment. Similar regulations have been implemented in other regions to reduce the environmental and health impact of electronic products [43,44]. In Uruguay, on the other hand, there are no legislative tools in place regulating the use of hazardous substances in consumer products; therefore, the composition of EEE entering the market is not controlled. The lack of regulation of the material entering the market results in the presence of hazardous materials, towards which there is insufficient knowledge and infrastructure for treatment.

In Uruguay, WEEE management is only covered as part of the Integrated Waste Management Law introduced in September 2019.

Overall, while both Uruguay and Scotland have mechanisms in place for WEEE management, Scotland's system is more extensive and aligned with the European Union standards, due to the former EU membership of the UK. However, Uruguay is also taking steps to improve its WEEE management practices, and the country's specific approach and progress is set to evolve in the near future.

3.5.2. WEEE Management Infrastructure

In Scotland, there are no reports on the volumes of WEEE plastics produced or managed on a national level. The main activities carried out after dismantling involve crushing and sink-and-float processes for separating the denser hazardous fraction (containing POPs) from the lighter non-hazardous fractions, based on material densities alone [8]. At the time of the study, it is reported by SEPA that no sites existed in Scotland to provide sorting services; therefore, all the recovered plastic is shipped to England. At a later stage, the non-hazardous fraction is sent for recycling, whether in the UK or abroad, and the hazardous fraction is incinerated. This is due to the UK POP regulation that states that it must be treated, to ensure that POPs are either destroyed or irreversibly transformed.

According to 2023 records from the Environment Ministry of Uruguay, most WEEE operators cover mainly logistical activities, dismantling, and recovery for treatment, in the country or for export. It should be noted that there is a considerable under-reporting of the quantities generated and recycled, due to the prevalence of informal collection, dismantling, and recycling activities, and the existing infrastructure is concentrated mainly in Montevideo [13].

As for plastics, the formally recovered fraction is exported for recycling in other countries, with reports of only 0.11 ton having been exported to Europe, and 0.09 ton to Asia, in 2019. Considering that the total amount of WEEE produced during the same year was 39 kt, and estimating that 30% was plastic, it is clear that the formally recovered mass is negligible.

As for the detailed POP content of materials in devices, the information is very scarce, although the POPs found in CRT and LCD monitors have been estimated to be 32 wt% and 0.15 wt%, respectively [45]. There are no treatment facilities in the country and POP plastics are not being identified and segregated. The current practice is to send all WEEE plastics suspected of containing POPs to landfill [31]. Alternatives are being evaluated for the treatment of this hazardous waste via the PREAL project [46]. More detailed data on the characteristics of the plastics recovered would allow for the improved management of this material.

3.5.3. Treatment Options in the Latin American Region

At the time of this study, most Latin American countries are in the process of developing standards for the management of WEEE plastics containing POPs, so the infrastructure available for their treatment is basic or non-existent, depending on the country [32]. Most WEEE plastics are exported outside the region as part of the whole WEEE, mainly to the United States of America, Belgium, Japan, Republic of Korea, the Netherlands, Canada, and China [47]. Common treatment options include mechanical and chemical recycling, as well as energy-recovery processes. Mechanical recycling comprises the sorting, shredding, and processing of plastic waste to produce raw materials that can be used to manufacture new products. Plastics with BFRs can be mechanically recycled if the BFR content is within acceptable limits. However, the presence of BFRs may limit the range of applications for the recycled plastic. Chemical recycling involves breaking down plastics into their monomers to produce new materials or fuels; this is the case for pyrolysis or gasification. These processes can potentially break down BFRs and other additives, enabling the recovery of plastic feedstock without the need for sorting or separation based on the BFR content. However, chemical recycling technologies are still being developed and are not widely available in Latin America. For instance, the PLAST2bCLEANED [48] and NON-TOX [49] projects funded by the European Union's Horizon 2020 programme researched and developed technology for the safe recycling of WEEE plastics, via separately recovering the polymer, bromine, and antimony trioxide fractions. Lastly, energy recovery allows plastic waste to be used for the generation of heat and/or electricity through its incineration. However, a minimum temperature of 850 °C and at least 2 s of gas residence time are required to break down BFRs [50] and minimize their release into the environment. Thus, it is essential to ensure that proper emission control measures are in place to capture and treat any pollutants emitted during the process.

In most Latin American countries, recovered items are disposed in landfill sites; which, in many cases, lack any secure lining to prevent the direct leaching of hazardous substances into the ground; or are incinerated in open spaces (uncontrolled burning).

4. Results

4.1. Bromine and Antimony Content: Classification

For Company 1, the 80 plastic samples were shown to have some level of bromination, with the highest being a LED TV manufactured in 2012. These samples also contained antimony, but in a lower percentage, with 22 samples (28%) showing non-detectable levels of Sb (LOD, Sb = 2 mg/kg).

For Company 2, out of the 80 samples, 19 showed Br concentrations below the detection limit (LOD, Br = 1 mg/kg), and the highest level corresponded to [Br] > 10 wt%. for samples manufactured between 2007 and 2017. As for Sb, the concentration was below the detection limit in 44 samples. All samples with Sb concentrations higher than those defined as classifying an item as hazardous (8300 mg/kg) simultaneously showed considerably high Br concentrations, ranging from 5.2 wt% to >10 wt%.

A summary of the median, maximum, and minimum concentrations of Br and Sb measured for each Company's samples are included in Table 4.

Table 4. The bromine and antimony concentrations determined via h-XRF.

		Median (mg/kg)	Max (wt%)	Min (mg/kg)
Bromine (ppm)	Company 1	762	>15%	<LOD
	Company 2	135	>10%	<LOD
Antimony (ppm)	Company 1	2104	>2.8%	53.5
	Company 2	<LOD	>6.2%	<LOD

Based on the set concentration limits presented in Table 2, the percentages for each category were calculated. As summarized in Figure 1, the samples analysed from Company

1 more frequently exceeded the Br and Sb concentration limits. The POP waste for Company 1 accounted for 28% of the samples, while for Company 2, the percentage was significantly lower, at 8%. As for recyclable plastics, in Company 1, this fraction corresponded to 49% of samples while, in Company 2, the percentage rose to 73%. The POPandHAZ fractions were relatively similar in both cases.

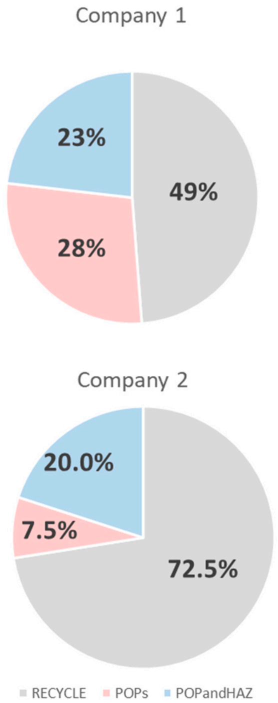

Figure 1. Classification of the plastics from Company 1 and 2 according to their Br and Sb concentrations.

4.2. Year of Manufacture

Information on the year of manufacture (YoM) was retrieved from the equipment when available and/or visible. These data were collected for 42 samples from Company 1, and 79 samples from Company 2. Figure 2 shows the number of items sampled by YoM, and, whilst in Company 1, the highest number of items was manufactured in 2012 and 2014, in Company 2, this average moved closer in time to 2017–2020. However, the distribution of the number of items per YoM in Scotland is more evenly distributed, ranging between 2007 and 2022.

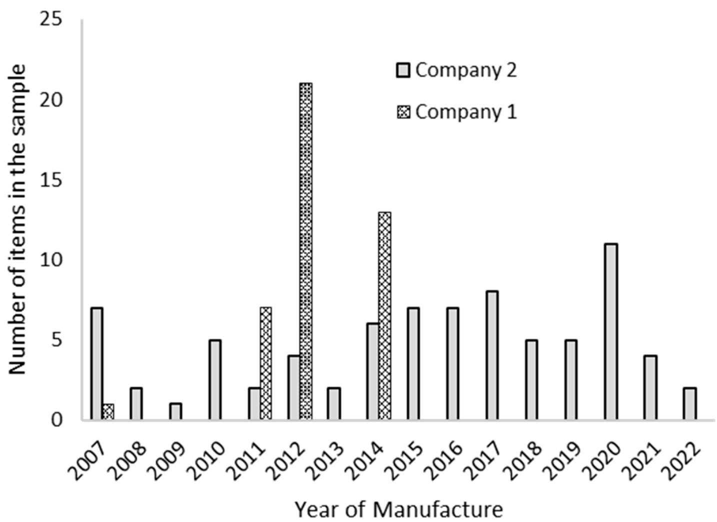

Figure 2. The year of manufacture of the equipment sampled.

Figure 3 presents a plot of the bromine concentration according to the year of manufacture. For reference, information on the years in which different POP brominated flame retardants were banned as part of the Stockholm Convention is included, together with the RoHS Directive's enforcement in Europe.

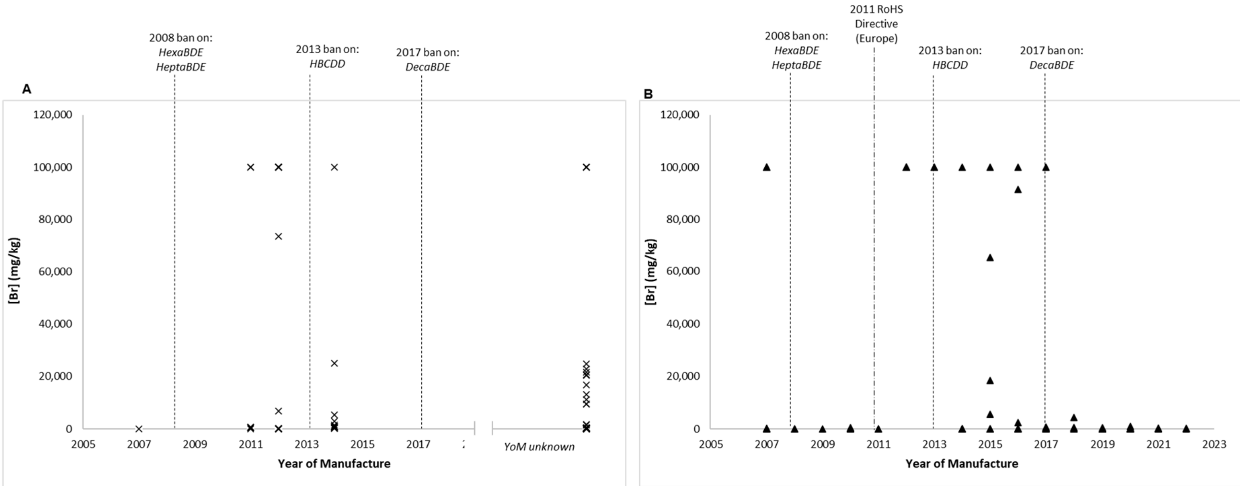

Figure 3. The variation in bromine concentration determined via h-XRF according to the YoM of the equipment. (**A**) Br concentration determined for items in Company 1 vs. Year of Manufacture. (**B**) Br concentration determined for items in Company 2 vs. Year of Manufacture.

4.3. Amount of Plastic Generated: An Estimate

The amounts of plastic generated in 2019 in both Uruguay and Scotland, in each category, were determined using the following factors: (i) the consideration that 30% of the mass of the waste monitors, screen, and display is plastic, (ii) the proportion (as %) determined for each classification category (Figure 1), and (iii) the volumes of devices generated in 2019 in Uruguay and Scotland (Table 3). The results are presented in Table 5.

Table 5. The estimated volumes of WEEE plastics generated in Uruguay and Scotland by category.

	Ton/Year (2019)		
	Uruguay	**Scotland**	**Difference**
Monitors, screens, and display devices	5613	3563	37%
Plastic	1684	1069	37%
Recyclable	821	775	6%
POPs	472	80	83%
POPandHAZ	390	214	45%

5. Discussion

Although the percentage of items with a known YoM in Company 1 was considerably lower, the compiled data show a clear delay in equipment disposal in Uruguay compared to Scotland. The results for Company 1 (Figure 3A) do not allow any conclusions to be made regarding the impact of the HexaBDE, HeptaBde, or HBCDD bans, as the majority of samples for which the YoM was retrieved had Br in concentrations higher than 800 mg/kg, indicating the likely presence of brominated flame retardants that could be attributed to POP compounds ([51–54]). Therefore, a priori, bans on certain compound defined within the Stockholm Convention do not seem to be effectively applied when the destination market for the equipment lacks the legislative tools to evaluate and penalize non-compliance.

The results for Company 2 (Figure 3B) show a different scenario, where the ban on HeptaBDE and HexaBDE appears to have been complied with. The RoHS directive does not seem to have had the expected impact on POP/BFR concentrations, as a considerable number of samples manufactured between 2011 and 2017 presented Br concentrations higher than 10 wt%. While it may be argued that this Br was found as TBBP-A, a non-POP brominated flame retardant, the marked descent in concentration after the ban of decaBDE in 2017 suggests that this was the brominated compound present up until that year.

Even though the volumes of waste display equipment generated yearly in both countries are relatively similar, there is an outstanding 83% difference between the estimated volumes of POP plastics. However, the volumes of recyclable plastics are not that different, as the lower percentage of samples classed under this category in Uruguay is compensated for by the higher volumes of equipment produced. As for the POPandHAZ fraction, the volume of plastics sorted as such in Uruguay would be almost twice that in Scotland.

The presence of flame retardants in plastics derived from WEEE poses three great challenges: interference with recycling, the emergence of alternatives, and global regulation. These are evidenced by the findings of this study, which demonstrate the disproportionate amounts of hazardous materials being shipped to markets with low regulatory control, such as Uruguay. Moreover, it is likely that this is the case in other parts of the world where legislation is also limited. The fact that no global regulation exists, and that each country/political community develops their own, directly impacts the international trade and harmonization of safety regulations. The latter puts developing countries at a disadvantage, which can be evidenced by the high levels of FRs determined in consumer products placed on the market.

We observed that the concentration of Br as a tracer of BFRs showed that, in Uruguay, WEEE plastics with Br concentrations above the limits established in the European regulations are very frequent, and less than 50% of the plastic from display equipment could be recycled. On the other hand, in Scotland, the data show the positive impact of the regulatory system, with more than 70% of the plastic being recyclable. It was also noted that, although the Stockholm Convention banned the production and application of certain brominated compounds, including flame retardants such as HBCDD, hexaBDE, heptaBDE, and decaBDE, high concentrations of bromine continued to be found in equipment placed on the market afterwards. We must also highlight that bromine may be associated with non-POP BFRs.

Table 6 illustrates the contrasts and potential advantages in the challenges faced in Uruguay and Scotland.

Table 6. Current challenges and opportunities for WEEE management: Uruguay vs. Scotland.

Aspect	Uruguay	Scotland
Material	Technological alternatives must be sought to cope with the higher volumes of POPs and hazardous waste, and greater management costs. The weaker economic development suggests that the availability of the necessary technology will not be immediate, or on an appropriate scale. This results in inefficient waste management or export, losing the opportunity to generate business and economic profit from resource recovery.	With support from the government for the innovation and development of new technologies, technically and economically feasible alternatives for the management of this unique type of waste are being sought.
Legislation	It would be key to develop and enforce legislation that regulates the presence and management of POPs in WEEE plastics, in order to protect the environment and public health. Ongoing efforts should be focused on developing regulation that includes control measures and restrictions on the characteristics of the products that are placed on the market.	Regulations put pressure on waste managers who must make large investments to comply with a demanding legislation that does not focus on controlling the problem, and only addresses the solution.

Table 6. *Cont.*

Aspect	Uruguay	Scotland
Waste management sector	It is necessary to provide support to the waste management sector, so that it can exist even after facing the higher management costs associated with complying with any standards. It is advisable to promote eco-design, to ensure the quality of the equipment placed on the market, as well as to allow users and managers to know what components it contains. It is necessary to ensure the implementation of a system for the collection, reuse, and recycling of end-of-life equipment.	
Sorting criteria	The screening of WEEE plastics for hazardous compounds, such as POPs, is a practice that should be widely adopted. One of the keys to the implementation of a screening technique on the industrial level is the speed of processing; thus, it is important to define the criteria (based on tracer elements, i.e., Br/Sb or chemical compounds) that will be used to validate the defined requirements and their implementation.	
Sorting technology	With relatively low investment and operating costs, XRF would be a suitable, cost-effective option to consider, with a capacity to determine Br/Sb concentations in less than 10 s, and with an approximate efficiency of 90% [55]. Further research on the effectiveness and efficiency of h-XRF for the identification of hazardous materials is still needed, as manufacturers are migrating the use of POP-BFRs to non-POP-BFRs.	

6. Conclusions

We have demonstrated the challenges of considering the implementation of comprehensive worldwide regulations for WEEE materials. However, in their absence, countries can work to align their regulations, share scientific data, and collaborate in addressing common concerns related to FRs, which can lead to the development of international guidelines and standards that retain fire safety priorities, yet minimize their potential environmental and human health impacts.

Our findings present evidence allowing the regulatory authorities of developing countries, such as Uruguay, to view a validated characterisation of one of the most important waste streams within WEEE. This can underpin the improvement of future WEEE regulations, promoting initiatives and investments to develop the necessary management infrastructure, including cross-border alternatives. Furthermore, comparison with a similar European country, such as Scotland, provides a reference case for the effectiveness of the restrictions defined in that country towards the management of WEEE, with evidence to encourage the application of similar goals to improve public safety.

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