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Leaching assessments of toxic metals in waste plasma display panel glass

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The plasma display panel (PDP) is rapidly becoming obsolete, contributing in large amounts to the electronic waste stream. In order to assess the potential for environmental pollution due to hazardous metals leached from PDP glass, standardized leaching procedures, chemical speciation assessments, and bioavailability tests were conducted. According to the Toxicity Characteristic Leaching Procedure (TCLP), arsenic in back glass was present at 4.46 ± 0.22 mg/L, close to its regulation limit of 5 mg/L. Zn is not available in the TCLP, but its TCLP leaching concentration in back glass is 102.96 ± 5.34 mg/L. This is because more than 90% of Zn is in the soluble and exchangeable and carbonate fraction. We did not detect significant levels of Ag, Ba, or Cu in the TCLP leachate, and the main fraction of Ag and Ba is residual, more than 95%, while the fraction distribution of Cu changes SEP by SEP. Ethylenediamine tetraacetic acid (EDTA)- and diethylenetriamine pentaacetic acid (DTPA)-extractable Ag, As, Ba, Cu, Zn, and Ni indicate a lower biohazards potential. These results show that, according to the EPA regulations, PDP glass may not be classified as hazardous waste because none of the metals exceeded their thresholds in PDP leachate. However, the concentrations of As and Zn should be lowered in the manufacturing process and finished product to avoid potential pollution problems.

Implications: The plasma display panel is rapidly becoming obsolete because of the liquid crystal display. In this study, the leachability of heavy metals contained in the waste plasma display panel glass was first examined by standardized leaching tests, typical chemical speciation assessments, and bioavailability tests, providing fundamental data for waste PDP glass recovery, recycling, and reuse.

Introduction

In recent years, there has been a significant product redesign in consumer electronics driven primarily by the demand for less bulky equipment with multiple capabilities. For example, cathode ray tube (CRT) monitors have been largely replaced by flat panel display (FPD) such as plasma display panel (PDP) and liquid crystal display (LCD) to accommodate the desire for smaller sizes and sophisticated functions. PDP has the advantage of creating a large, thin, wide-viewing-angle, high-resolution display screen (Li et al., 2011), thus increasing greatly in the global consumer market, especially in large-size televisions (>42-inch diagonal screens). In 2001, approximately 300,000 PDPs were sold worldwide, but the market grew to 13.9 million units in 2010 (Boeuf, 2003; HIS iSuppli Research, 2012). Meanwhile, the infrastructure to recover and properly recycle defunct PDPs at the end of their useful life is not uniformly developed, leading to potential stockpiling and inappropriate disposal with adverse consequences for environmental pollution and human health.

Waste PDPs present a concern for environmental quality because of hazardous material constituents. For example,

PDP glass contains the metals barium and strontium in the form of oxides in the glass plates that shield people from x-rays (Figure A in Supplemental Material) (Lim et al., 2010; Méar et al., 2006); phosphors, which contain Zn, Mn, As, Ba, and real earth metals, are used to produce visible light (Kim et al., 2000).

Predicting the potential environment impacts of toxic materials contained in solid waste, such as leachability, environmental mobility, and bioavailability, requires the evaluation of the short- and long-term fates of the materials and their potential interactions with ecosystem components (Pueyo et al., 2008). For metals, total concentration and leachability should be considered, but it is also more important to assess chemical speciation because availability, mobility, (phyto)toxicity, and potential toxicity risks are strongly affected by the chemical manner of appearance of elements, the so-called speciation (Van Herreweghe et al., 2003). To predict metallic compound speciation impacts, sequential extractions procedures schemes (SEPs) reported by the Community Bureau of Reference (BCR) protocol of the European Standards Measurements and Testing Program

(Rauret et al., 2000; Ure et al., 1993), Tessier (Tessier et al., 1979), and Grimalt (Alvarez et al., 2001) have been developed to determine the solid-phase speciation of heavy metals in contaminated soils (Alvarez et al., 2001; Pueyo et al., 2008; Rauret et al., 2000; Tessier et al., 1979; Ure et al., 1993; Van Herreweghe et al., 2003), in medical waste incineration ashes (Zhao et al., 2010; Zhao et al., 2009), and in municipal solid waste incineration ashes (Huang et al., 2007) and industrial waste (Dold, 2003; Van Herck et al., 2001).

The objectives of this study are (i) to assess toxic metal leachability from waste PDP glass in order to determine whether these products are to be categorized as hazardous waste under hazardous waste regulations in China (MEP China, 2007) and the United States (EPA, 1996), (ii) to investigate leachable metal compound speciation based on three typical sequential extraction procedures reported by the Community Bureau of Reference (BCR) protocol of the European Standards Measurements and Testing Program (Rauret et al., 2000; Ure et al., 1993), Tessier (Tessier et al., 1979), and Grimalt (Alvarez et al., 2001), (iii) to understand the relationship between the leaching toxicity and chemical speciation by analysis TCLP leaching concentrations of heavy metals in waste PDP glass and residues after extracting each fraction by the three SEPs, and (iv) to assess the bioavailability of metals in PDPs according the methods reported by Lindsay et al. (Alvarez et al., 2001) and Wear et al. (1968). Satisfaction of these objectives will provide fundamental data for waste PDP glass recovery, recycling, and reuse and will supplement the information needed to develop sustainable international e-waste management policies and to guide design-for-the-environment strategies focusing on mass-marketed electronic products.

Materials and Methods

Sample collection and preparation

Waste PDP glass samples were provided by Changhong (High-Tech Park, Mianyang, Sichuan, China; <http://www.changhong.com>), the only PDP producer and the largest manufacturer of televisions in China. Five kilograms PDP glass was crushed to a particle diameter of 9.5 mm, as required by toxicity characteristic leaching procedures. After homogenization and partitioning, the samples were subjected to a dry ball mill and sieved to smaller than

80 mesh (0.177 mm) for the three sequential extraction procedures and bioavailability analysis.

Total metals analysis

The prepared sample particles were digested by an $\text{HNO}_3\text{-HClO}_4\text{-HF}$ system (Yamasaki, 1997), as described by Zhang et al. (2002). Specifically, 0.5 g of dry sample was weighed into a Teflon beaker, and 2.5 mL HNO_3 and 2.5 mL HClO_4 were added and heated for 2–3 hr; after cooling, 2.5 mL HClO_4 and 5 mL HF were added and heated for 15 min; then 5 mL HF was added until the residue became dry; and the residue was dissolved using 5 mL HNO_3 and diluted 1000 times. Then the chemical composition was determined by inductively coupled plasma-optical emission spectrometry (ICP-OES, Perkin-Elmer). According to hazardous waste regulations in China and the United States, five metals, Ag, As, Ba, Cu, and Zn, were selected as the target metals in this study.

Toxicity leaching procedures of the United States and China

Two regulated leaching test procedures, HJ/T 299-2007 of China (MEP China, 2007) and TCLP (Method 1311; 40 CFR §261.24) of the EPA (1992), shown in Table 1, were employed to assess the potential hazardous classification of waste PDP glass. For each analysis, 1 g of each sample and 10/20 mL extraction fluid according to the leaching procedures were added to a series of extraction bottles. The bottles were then placed on a rotary extractor and shaken at 30 rpm for 18 ± 2 hr. At the end of the extraction, the leachate was filtered through a glass-fiber filter of 0.45 μm pore size and preserved using 2 mL of nitric acid before being analyzed by ICP-OES.

Sequential extraction procedures

Chemical speciation of the selected metals in the waste PDP glass was determined by three typical sequential extraction procedures (Figure 1). The first procedure is the three steps of BCR protocol of the European Standards Measurements and Testing Program (Rauret et al., 2000; Ure et al., 1993). The second comprises five steps and was an adaptation of the procedure proposed by Tessier et al. (1979), and the third procedure has six steps suggested by Grimalt (Alvarez et al., 2001). For comparison, chemical speciation of the three

Table 1. Toxicity characteristic leaching procedure of United States and China

	Extractant	L/S ratio (mL/mg)	Time and temperature
United States	1: Add 5.7 mL glacial $\text{CH}_3\text{CH}_2\text{OOH}$ to 500 mL of reagent water, add 64.3 mL of 1 N NaOH, and dilute to a volume of 1 L, pH 4.93 ± 0.05 . 2: Dilute 5.7 mL glacial $\text{CH}_3\text{CH}_2\text{OOH}$ with reagent water to a volume of 1 L, and the pH of this fluid will be $2.88 + 0.05$.	20	18 ± 2 hr at $23 \pm 2^\circ\text{C}$
China	$m(\text{H}_2\text{SO}_4)/m(\text{HNO}_3) = 2/1$, pH 3.20 ± 0.05	10	18 ± 2 hr at $23 \pm 2^\circ\text{C}$

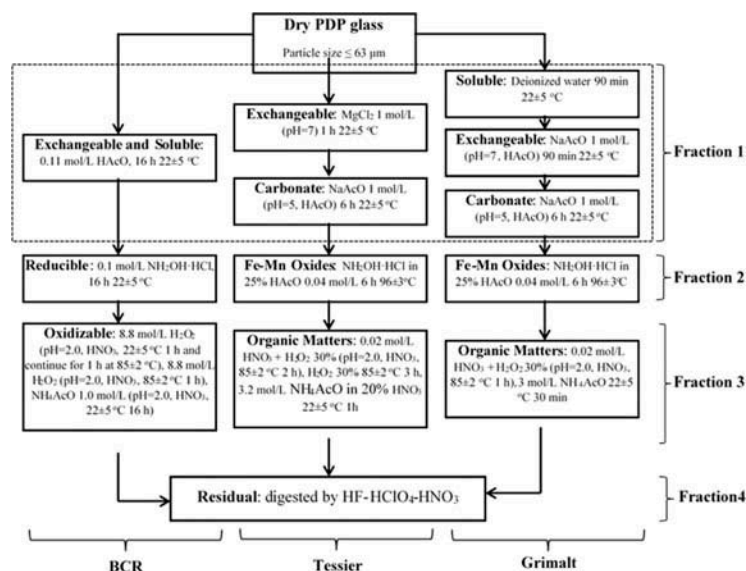


Figure 1. Flow chart of sequential extract procedure of BCR, Tessier, and Grimalt.

sequential extraction procedures was classified in four fractions: Fraction 1, the first step of BCR or the first and second step of Tessier or the first three steps of Grimalt; Fraction 2, the followed single step of Fraction 1; Fraction 3, the followed single step of Fraction 2; and Fraction 4, residual, the last step of each SEP.

All the procedures were carried out in 50 mL polypropylene centrifuge tubes provided with screw stoppers except the final step, which was digested according to the previous total analysis and conducted in polytetrafluorethylene (PTFE) containers. The extracts were separated from the solid residue first by centrifugation at 3000 rpm for 30 min and then by filtration using a 0.45-μm glass-fiber filter. The residue was washed with distilled, deionized water and the washings discarded before continuing the extraction sequence. Control blanks were processed simultaneously at all stages of the procedure. Only control blank values below the instrumental limits of detection were considered acceptable.

Bioavailability

A diethylenetriamine pentaacetic acid (DTPA) extract test was conducted according to Lindsay and Norvell (1978). According to the method, 10 g sample was mixed with 20 mL 0.005 mol/L DTPA, 0.01 mol/L CaCl₂ was added, the pH of the suspension was adjusted to 7.3 in a 50-mL plastic centrifuge tube, and the suspension was shaken for 2 hr. An ethylenediamine tetraacetic acid (EDTA) extract test was conducted according to the specifications of the Wear and Evans method (Wear et al., 1968): 2.0 g ash sample was mixed with 20 mL 0.05 mol/L EDTA and its pH was adjusted with ammonia solution to 7.0 in a 50-mL plastic centrifuge tube, and the suspension was shaken for 1 hr. For all extraction procedures, after shaking, the suspensions were centrifuged at 3000 rpm for 20 min and the supernatant was filtered through a 0.45-μm glass-fiber filter prior to determination. All the experiments

were repeated three times, and mean values and ranges are reported in the tables and figures.

Results and Discussion

Metal content

Waste PDP glass, both front and back, was first analyzed by x-ray fluorescence (XRF), and the results are reported in Table 2. Metal concentration data gathered through ICP-OES showed no significant differences in front and back glass, and specifically, they are both lead (Pb) free, consistent with recent international regulations to phase Pb out of electronic products. Barium and strontium, contained in the front and back glass, are used instead of Pb to shield x-rays generated in the PDP TVs (Mear et al., 2006).

The compositions of these two sectional glasses are different mainly in two aspects. First, silicon concentration in front glass (53.01%) is much higher than in back glass (31.10%). Second, the concentrations of Y, Gd, Zn, Mn, As, Zr, and Ba were higher in back glass because the inner surface of back glass is coated with phosphors, which consist of, for example, red (Y, Gd)BO₃:Eu and Y₂O₃:Eu, green Zn₂SiO₄:Mn, (Y, Gd)BO₃:Tb, and BaAl₁₂O₁₉:Mn, and blue BaMgAl₁₀O₁₇:Eu and CaMgSiO₆:Eu (Kim et al., 2000), whereas the front glass is not coated with phosphors.

Hazardous waste classification

The results of toxicity leaching assessment of both front and back PDP glass, conducted according the standardized test procedures of China and the United States, are reported in Table 3. We did not detect Ag in the leachates according to both TCLP and HJ/T 299-2007, and all the concentrations of metals examined are below their regulation limits, although TCLP leaching concentration of Zn in back glass is 102.96 ±

Table 2. Chemical composition of waste plasma display glass by XRF

Front glass	Oxide	Na ₂ O	MgO	Al ₂ O ₃	SiO ₂	P ₂ O ₅	SO ₃	K ₂ O	CaO	TiO ₂	Fe ₂ O ₃	
	wt. %	3.99	1.79	6.26	53.01	0.02	0.10	6.02	5.04	0.79	0.16	
	Oxide	ZnO	Rb ₂ O	SrO	Y ₂ O ₃	ZrO ₂	Ag ₂ O	BaO	HfO ₂	Bi ₂ O ₃	Co ₃ O ₄	
	wt. %	0.79	0.01	7.78	0.02	3.30	0.23	8.97	0.05	1.63	0.03	
Back glass	Oxide	Na ₂ O	MgO	Al ₂ O ₃	SiO ₂	SO ₃	K ₂ O	CaO	TiO ₂	Fe ₂ O ₃	HfO ₂	Bi ₂ O ₃
	wt. %	0.56	0.40	3.82	31.10	0.36	6.03	5.51	1.17	0.47	0.07	5.10
	Oxide	CuO	ZnO	As ₂ O ₃	Rb ₂ O	SrO	Y ₂ O ₃	ZrO ₂	Ag ₂ O	BaO	Gd ₂ O ₃	
	wt. %	0.07	9.71	0.68	1.96	10.16	2.04	4.47	1.19	13.52	1.57	

5.34 mg/L, higher than the regulation limit of China 100 mg/L, but Zn is not available in TCLP. According to these results, waste PDP glass should not be classified as hazardous waste in China and the United States, but the results also point to inconsistencies in international regulatory policies on hazardous waste. It is also noteworthy that the concentration of As in back glass is 4.46 ± 0.22 mg/L, very close to the TCLP threshold of 5 mg/L, providing a potential threat to the environment and human health. In addition, toxic metal leaching concentrations of front glass are much lower than those of back glass, which provides an opportunity for improvements in material selection for product redesign to reduce overall risk of toxic hazards in e-waste.

For all metals, Ag, As, Ba, Cu, and Zn, all the concentrations determined in leachates tested by TCLP are higher than those obtained by HJ/T 299-2007 (Table 2). For example, Zn in the back glass for TCLP is 102.96 ± 5.34 mg/L, while that for HJ/T 299-2007 is only 35.97 ± 2.12 mg/L, about one-third of the former. As shown in Table 1, with the data from toxicity leaching procedures adopted by China and the EPA, we conclude that the test conditions used in TCLP are much more aggressive than those used in HJ/T 299-2007 (Lincoln et al., 2007), because TCLP, which simulates the toxic substances migration process from landfill leachate, caused by solid waste and municipal waste co-disposal, to groundwater (EPA), aims at protecting groundwater, and HJ/T 299-2007 is based on the same migration process but stresses acid rain and improper landfill disposals. Another difference in the regulatory and test procedures of the two countries is that only eight heavy metals, Ag, As, Ba, Cd, Cr, Hg, Pb, and Se, are included in TCLP, while HJ/T 299-2007 enlarges the set to four other heavy metals, Be, Cu, Ni, and Zn.

Effects of chemical speciation

We examined only waste PDP back glass for chemical speciation assessments because we had determined that the front glass showed a relative low leaching of toxic metals. For example, the highest leaching concentration of metal from the front glass was for Zn, which is 3.68 mg/L for HJ/T 299-2007, only 3.68% of its limit 100 mg/L. Table 4 summarizes the data for extracted metals by the three sequential extraction procedures. The results based on the HF-HClO₄-HNO₃ digestion system are compared with the sum of the extracted metals from the three fractions and residual. There were no significant differences between the total metals and the sum of extracted metals for SEPs suggested by BCR and Tessier, indicating the high quality of the results obtained (relative errors are within $\pm 20\%$; Rauret et al., 2000). In contrast, SEP reported by Grimalt was not stable because that study reported relative errors of metal recovery rate of -43.38% to 10.68% . This means that the SEP method reported by Grimalt may not be suitable for analyzing the behavior of metals contained in e-waste, although it is commonly used in the analysis of contaminated soil (Alvarez et al., 2001), just as are SEPs proposed by BCR and Tessier (Rauret et al., 2000; Tessier et al., 1979; Ure et al., 1993).

Figure 2 shows the three sequential extraction results of Ag, As, Ba, Cu, and Zn in the examined waste PDP back glass, and all the data are reported in Table A in the Supplemental Materials. The distribution patterns of Zn and Cu in the waste PDP back glass are quite different among the three SEPs. For example, the fraction distribution of Zn obtained by BCR is in the sequence of Fraction 1 > Fraction 2 > Fraction 3 > Fraction 4, and it changes to

Table 3. Results of the leaching test of EPA's TCLP and China's HJ/TSA and China

Heavy metal	HJ/T 299-2007, mg/L		TCLP, mg/L		Threshold of HJ/T 299-2007, mg/L	TCLP threshold, mg/L
	Front glass	Back glass	Front glass	Back glass		
Zn	3.68 ± 0.08	35.97 ± 2.12	10.25 ± 0.35	102.96 ± 5.34	100	N/A
Cu	ND	0.03 ± 0.01	ND	0.42 ± 0.02	100	N/A
Ag	ND	ND	ND	ND	5	5
Ba	0.02 ± 0.01	0.04 ± 0.01	1.51 ± 0.02	6.12 ± 0.21	100	100
As	ND	0.75 ± 0.01	ND	4.46 ± 0.22	5	5

Notes: N/A, not applicable; ND, not detected.

Table 4. Extraction efficiencies of metals with three analysis methods

Element	Pseudo total, mg kg ⁻¹	BCR		Tessier		Grimalt	
		Σ steps + residual, mg kg ⁻¹	Relative error, %	Σ steps + residual, mg kg ⁻¹	Relative error, %	Σ steps + residual, mg kg ⁻¹	Relative error, %
Zn	78014.00 ± 390.07	77135.01 ± 356.75	-1.13	75215.82 ± 360.78	-3.59	44095.12 ± 257.86	-43.48
Cu	55.92 ± 2.79	59.53 ± 2.45	6.46	60.66 ± 2.76	8.48	53.16 ± 3.57	-4.94
Ag	11078.46 ± 153.93	9980.00 ± 159.00	-9.92	9430.03 ± 175.31	-14.88	8450.60 ± 160.97	-23.72
Ba	121091.87 ± 605.45	116966.92 ± 548.34	-3.41	123854.08 ± 567.45	2.28	112708.85 ± 678.69	-6.92
As	135.92 ± 5.79	148.57 ± 4.42	9.31	150.76 ± 4.45	10.92	150.44 ± 4.34	10.68

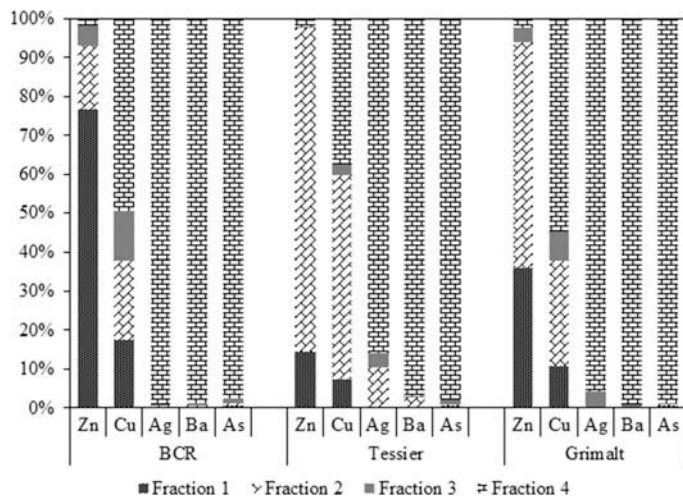


Figure 2. Distribution patterns of metals among different fractions for each sequential extraction scheme.

Fraction 2 > Fraction 1 > Fraction 4 > Fraction 3 and Fraction 2 > Fraction 1 > Fraction 3 > Fraction 4 for SEPs proposed by Tessier and Grimalt, respectively. In contrast, we found no significant differences in the distribution of the other three metals, Ag, As, and Ba.

However, Zn bound to soluble, exchangeable, and carbonate (Fraction 1) and reducible Fe–Mn oxides (Fraction 2), 41.45–73.49 g/kg, comprise almost over 95% of zinc's total amount. Ag, As, and Ba in these two fractions are 0.22–10.53%, 0.73–1.27%, and 0.33–2.77%, respectively. The percentage of Cu bound to these two fractions for the three SEPs is relatively high, in the range of 37.88–59.72%. However, the sum of the two extractable fractions is very low, 20.19–36.23 mg/kg. Previous studies reported that the metal content in the exchangeable and carbonate fractions (the mobile fractions) is indicative of the potential availability and leaching of metals (Elliott et al., 1990; Sukandar et al., 2006), and it has been reported that metals associated with the Fe–Mn oxide fraction could not be immediately chemical reactive, but their mobility and availability could be potentially affected by the change of environmental conditions (Tan et al., 1997). Thus, the amounts of various metals in these two fractions indicate that Zn has the highest leaching potential and Ag, As, and Ba are negligible. The percentages of metals of Fraction 3 (oxidizable and organic matters) in the waste PDP back glass are low since there are no organic chemical constituents. The residual fraction (Fraction 4, stable fraction) is generally less mobile, and thus difficult to leach out into the environment. The proportions of Ag, As, and Ba bound to the residual fractions are much higher than those of the other metals (85.74–99.22%). Accordingly, it is reasonable to consider these metals to be less mobile and to have low environmental availability. Therefore, according to the chemical speciation analysis provided by the three SEPs, we determined that Zn in the waste PDP back glass poses comparatively higher leaching risk to the environment, whereas Ag, As, Ba, and Cu do not.

Chemical speciation tests combined with TCLP

To better understand the relationship between the leaching toxicity and chemical speciation, residues of waste PDP back glass after extracting Fractions 1, 2, and 3 were further analyzed by TCLP for each of the three SEPs. The results from these experiments are reported in Figure 3, and the full data are presented in Table B in the Supplemental Material.

We did not detect Ag during these serial experiments. TCLP leachate concentrations of Cu and Zn in waste PDP back glass and the corresponding residues after extracting Fractions 1, 2, and 3, for the three SEPs, decreased concurrently with the extraction of each fraction. For example, after extracting each fraction by BCR, TCLP leaching concentration of Zn decreased from 102.96 mg/L to 32.73, 6.05, and 0.14 mg/L. Therefore, the leaching toxicity of Zn caused by Fractions 1, 2, 3, and 4 are 70.23 mg/L, 26.88 mg/L, 5.91 mg/L, and 0.14 mg/L, respectively. This result demonstrates that Fraction 1 has the highest leaching risk and the residual the lowest, while other chemical speciation decrease as the steps sequence. Moreover, TCLP leaching toxicity is mainly caused by Fraction 1 and Fraction 2. After removing Fractions 1 and 2, TCLP leaching concentration of Zn was reduced from 102.96 mg/L to 6.05 mg/L, 0.91 mg/L, and 1.66 mg/L for BCR, Tessier, and Gramlt procedures, respectively. This means that according to TCLP, more than 95% of leaching toxicity of Zn could be removed through interactions with other components of the ecosystem.

For Ba, the results are similar to the results for Cu and Zn except the residues after Fraction 1 for both Tessier and Gramlt procedures are 24.16 mg/L and 23.47 mg/L, respectively—much higher than the 6.12 mg/L concentration of Ba determined through TCLP assessment of the original waste PDP back glass. This result indicates that Ba in the residue after extracting Fraction 1 becomes much easier to leach out than it is in the original waste PDP glass. The implication is that the mobility and availability of Fractions 2 and 3 are influenced by environmental conditions.

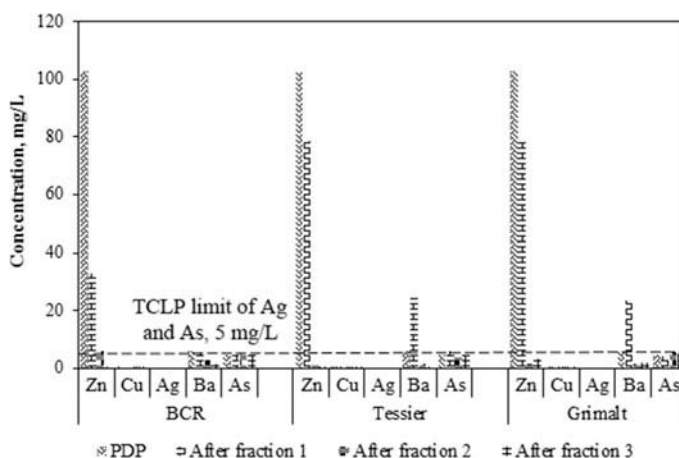


Figure 3. TCLP-extracted concentrations of heavy metals for waste PDP glass and residues after extracting Fractions 1, 2, and 3 by BCR, Tessier, and Grimalt sequential extraction method.

Across the three sequential extraction procedures, no significant difference was observed between TCLP leaching concentration of As in waste PDP back glass and in the residues after each fraction, which ranged between 4.30 mg/L and 6.02 mg/L. This means that the main leaching toxicity of As is caused by its residual fraction, which is different from the other metals that we investigated. A possible reason is that the residual fractions of As in all three fractionation procedures account for more than 97% of the total amount detected, and there are special SEPs developed for As (Keon et al., 2001) to account for its particularly reactive properties (Dold, 2003; Huang et al., 2007; Zhao et al., 2010; Zhao et al., 2009). Additionally, although the mean concentration of As detected in the TCLP leachate (4.46 ± 0.22 mg/L) was below the regulation limit, the concentration of As in the residues after each fraction for the three SEPs could exceed the regulation limit of 5 mg/L. Thus, As makes waste PDP back glass a real potential threat to the environment and human health.

Metal bioavailability

The results of extractable metal concentrations in the waste PDP glass using DTPA and EDTA are reported in Figure 4, and the full data are presented in Table C in the Supplemental Material. In general, DTPA-extractable metals are higher than those of EDTA. This could be due to the possibility that the extraction capacity of EDTA is stronger than that of DTPA, as reported by previous studies (Gupta et al., 2007). EDTA- and DTPA-extractable concentrations of Ag and Ba are very low, accounting for 0.001%, 0.001%, 0.18%, and 0.03% of the total concentration, respectively. In comparison, EDTA- and DTPA-extractable concentrations of Zn and Cu are much larger than those of Ag and Ba, and are 1.09%, 0.20%, 7.28%, and 5.19% of the total concentration, respectively. EDTA- and DTPA-extractable concentrations of As are the highest, 33.07% and 23.46%. EDTA- and DTPA-extractable Ag, As, Ba, Cu, and Zn were in the range of 0.08–851.05 mg/kg. The results revealed that the bioavailability of leached Ag, As, Ba, Cu, and Zn from PDP glass are relatively low.

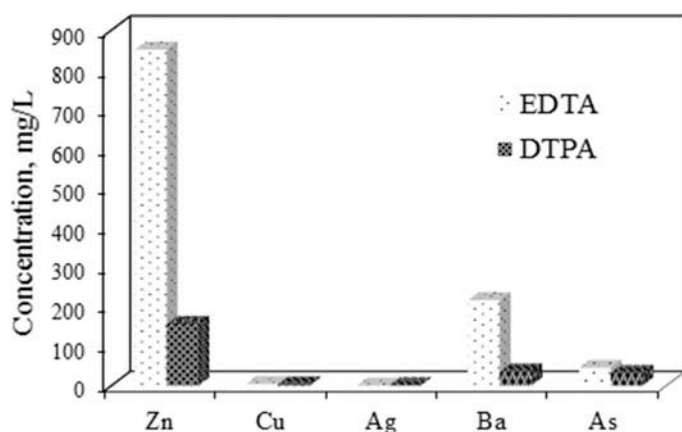


Figure 4. EDTA- and DTPA-extractable metals in waste PDP glass.

Summary

Through this research, we determined that waste PDP front glass and back glass should be treated differently because the front glass is not hazardous, while the back glass has hazardous waste potential due to the content of arsenic and zinc. In experiments simulating landfill conditions, the mean concentration of As measured in glass leachate is 4.46 ± 0.22 mg/L, close to its regulation limit of 5 mg/L, while Zn is 102.96 ± 5.34 mg/L, higher than the regulation limit in China of 100 mg/L, though Zn is not available in the hazardous regulation of the EPA because more than 90% Zn mainly existed in a fraction easy to leach out, the soluble, exchangeable, and carbonate fraction, contributing more than 95% to the TCLP leaching concentration. It is interesting to note that other than arsenic, real earth elements contained in the phosphors, coated on the back glass, are not of concern in part because of the lack of regulatory policies. These results can be used to guide the recovery, recycling, and reuse policy development regarding manufacturing and product design practices. Our results also reveal important differences in the international regulatory policies that may create confusion in the classification of hazardous waste consistently across regions. In addition, there is a need for further investigation into the potential environmental and human health impacts associated with the toxicity of real earth elements that are not currently included in regulatory policies but are increasingly used in electronic products.

Supplemental Materials

Supplemental data for this article can be accessed at <http://dx.doi.org/10.1080/10962247.2015.1016634>.

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