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Characterizing the environmental implications of the recycling of non-metallic fractions from waste printed circuit boards

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ABSTRACT

Non-metallic fractions (NMFs), which make up almost three fourths (by weight) of waste printed circuit boards, have become a matter of great concern for e-waste recyclers, because most of them contain hazardous substances with low utilization value. This study used an advanced Sales Obsolescence Model approach to quantify the generation and flows of non-metallic fractions in China, and to examine the potential environmental impacts associated with both the fractions themselves, and their end-of-life processing activities: disposal into landfills or incineration, and recycling via physical or chemical methods. The results show that approximately 201,000 tons (one time standard deviation: 67,000) of scrap non-metallic fractions were expected to be generated in 2015, and that this amount could increase to 279,000 tons by 2020. Both our own analysis and a systematic review of existing studies on the hazardous characterization of printed circuit boards waste, non-metallic fractions, and their recycling and disposal activities, indicate the threat of environmental pollution, from heavy metals, brominated flame retardants and secondary persistent organic pollutants, particularly dioxins.

1. Introduction

Over the past few decades, a great deal of effort has been directed toward the promotion of environmentally sound management of electronic waste (e-waste), worldwide. The treatment of e-waste, however, is still a significant problem in China (Duan et al., 2016). Many Chinese recyclers restrict their activities to dismantling and separation, or focus on specific types or selected components of e-waste—particularly those yielding the most profit. For example, the major force driving e-waste recycling is the value of the metallic fractions (MFs) contained in waste printed circuit boards (PCBs) (Zhang and Zhang, 2014; Ghosh et al., 2015). The non-metallic fractions (NMFs), which account for almost 70 wt % of waste PCBs, have hence become problematic. This situation is very similar to the dilemma of leaded CRT glass: (1) further recycling or reuse, which could produce positive environmental impacts, is difficult, and yet (2) simply storing the increasing amount of waste generated is becoming unfeasible.

A number of studies have focused on the reuse of NMFs as composite fillings (Guo et al., 2009b; Zheng et al., 2009; Wang et al., 2010; Duan et al., 2010). Guo et al. (2008a) used NMFs to produce several types of value-added composite products such as sewer grates, park benches, and fences, using resin as a bonding agent. NMF products could also be used in place of wooden composite products, since they have excellent mechanical performance and chemical resistance (Guo et al., 2009a). In addition, NMFs have been studied as an innovative modifier to improve the performance of asphalt (Guo et al., 2008b). Duan et al. (2010) examined the reuse of comminuted glass-fiber-reinforced resin (NMFs) with various granularities, gathered from printed circuit manufacturing residues, to produce reinforced resin composite; Hadi et al. (2013, 2015) studied the feasibility of using NMFs as an adsorbent to remove toxic heavy metals (charged ions); Ke et al. (2013) attempted to prepare porous carbons with NMFs, using chemical and physical activation; and Li et al. (2014) used image forces to

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separate resin powder and fiberglass powder from NMFs during a corona electrostatic separation process. In practice, however, most NMFs are still being kept in storage, disposed of into landfills, or incinerated, because industrial applications and other uses for recycled NMFs either are unprofitable or raise environmental concerns.

Regarding the environmental impacts, however, there has been relatively little research to investigate the pollution associated with NMF reuse or disposal. Guo et al. (2011) examined volatile organic compounds and metal leaching from three kinds of composite products made from NMF fillings. Muniyandi et al. (2013) studied the mechanical, morphological, thermal and metal leaching properties of HDPE/NMFs composites. While these results indicated that the NMFs contained in the composite products were not a serious concern in terms of environmental assessment, based upon VOC tests or leaching characteristics examination, the diversity of the NMFs that might contain toxic substances has not been fully considered, since there are a variety of types of PCBs and substrates. In addition, there has been no evaluation of the halogenated flame retardants and their impacts, such as the polybrominated diphenyl ethers (PBDEs), new Persistent Organic Pollutants, (POPs), or tetrabromobisphenol (TBBPA, a significant precursor of brominated dioxin formation).

This study therefore focused on the generation and flows of NMFs in China, using an advanced Sales Obsolescence Model (SOM) approach to reveal the environmental implications from processing NMFs, including disposal into landfills, incineration, and recycling via physical or chemical methods.

2. Methods

2.1. Estimation approach to non-metallic fractions generation

Estimating and forecasting e-waste generation, using a number of different methods, is a growing field of study, worldwide (Ravi, 2012; Dwivedy and Mittal, 2012; Duan et al., 2013; Petridis et al., 2016). Examining published statistics about stocks of electrical and electronic products, or extrapolating such statistics from in-depth case studies and surveys, have resulted in a few estimates or predictions. There have also been several studies quantifying e-waste generation in China (Li et al., 2006; Yang et al., 2008; Zhang et al., 2012; Wang et al., 2013b; Duan et al., 2016; Song et al., 2016). All of the current estimates and developed approaches, however, have been restricted to specific e-waste types. There has been no study characterizing the generation of scrap PCBs or NMFs from e-waste, or their flows. An accurate estimate of e-waste generation, however, is a prerequisite to arriving at estimates of NMF generation.

In order to provide more quantitative data on NMFs in China, one objective of this study was to chose robust methodologies for quantifying the generation of e-waste, PCBs and NMFs in China. Consequently, the approach known as the Sales Obsolescence Model (SOM), which was developed by Miller and Duan (2013) to calculate the quantities of e-waste generation and flows in a case study in the United States, seems the most promising method to dynamically characterize these generations. Accordingly, this approach was updated and then employed to estimate the e-waste flows in China (Duan et al., 2016). Based on the calculation of e-waste generation, this more advanced SOM (introduced in the next section) was employed to quantify the PCBs and NMFs. A detailed introduction and framework for this SOM is contained in the Supporting Information.

The SOM method addresses data uncertainties and assumptions, and can extrapolate future trends. This study starts by defining the products n, 11 *in total*): TVs; cell phones; laptop and desktop computers; refrigerators; washing machines; air conditioners; and other large home appliances (LHAs).

The SOM method for quantification and prediction includes the following steps:

1. Determine the sales volume of each electrical and electronic product over a given time period.

Equation 1: Calculation of sales data

$$S_n = P_n - E_n + I_n$$

where S_n means sales volume; P_n is the production Volume; E_n is the export volume; I_n is the import volume; and n is the year.

Equation 2: Prediction model for annual sales

$$Y = \beta_0 + \beta_1 X + \beta_2 X^2 \ldots + \varepsilon$$

where Y is the dependent variable; β_0 is the intercept; X is the independent variable; β_1 , β_2 are regression parameters; and ε is residuals.

2. Determine the lifespan of each product over a given time period.

The SOM method incorporates several path lengths (described in detail in the Supporting Information), which, along with the overall weighted mean of the lifespans for all six paths, are expressed in Equation 3.

Equation 3: Overall weighted mean of lifespan for all paths (six in total) ϖ

$$\mu_{Overall} = \sum_{\varpi=1}^{6} P(\varpi)^{*}\mu_{\varpi}$$

where $\mu_{Overall}$ is the overall weighted mean lifespan; $P(\varpi)$ is the Mean Path Probability; μ_{ϖ} is the Mean Path Length; and ϖ is the Six Paths.

3. Determine the fractions of each type of electrical or electronic product by means of 'sizes' (n) distribution (data acquisition method can be found in the Supporting Information).
4. Determine the PCB and NMF compositions of the 11 types of products.

As shown in Table S14, the weight fractions of the PCBs contained in each type of electrical or electronic product, and the corresponding content of NMFs in the PCBs, were determined by extensive review of existing studies and our own dismantling experiments. Uncertainty is incorporated into the SOM in order to take data inconsistency into account. Specifically, we used an experiential dataset of the NMFs contained in the PCBs, which specified the amount as 70% wt (, with an assumed COV of 50%).

5. Calculate the total e-waste quantity generated in the given period, and then calculate the weight of generated NMFs by multiplying the mass fraction of PCBs and the fraction of NMFs, respectively, by the quantities. Detailed calculations can be found in the Supporting Information (Section 1.5).

Equation (4) was used to calculate the e-waste amount. The quantities of PCBs and NMFs can be further estimated by incorporating the mass fractions and contents (Equations 5 and 6).

Equation 4: Quantity of e-waste generated in year *y*