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Environmental emission analysis of a waste printed circuit board-derived adsorbent production process

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HIGHLIGHTS

- Systematic analysis of all emission streams and established mass balance of reaction reagents, bromide and carbon.
- Limited difficulties in emission treatment due to sole destination of pollutants.
- Excellent environmental sustainability by bromide recovery from the Washing Liquid.
- Provide evaluation criteria for waste recycling process development.

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ABSTRACT

The short life span of electrical and electronic equipments (EEE) produces a tremendous amount of waste electrical and electronic equipments (WEEE) globally at an overwhelming rate. Currently, the recycling of waste printed circuit board (WPCB) is an emerging and sensitive environmental issue since traditional treatment methods have been proved to be inappropriate. Also, the recovery of valuable components from WPCB is limited by the environmental emissions from the recycling process, which have been seriously neglected by the research community before. To analyze the environmental emission impacts and set evaluation criteria, a newly developed aluminosilicate adsorbent production process is discussed in this work. It is proved to be capable to recycle the NMF of WPCB as the feedstock of the functionalization process. Besides, the mass balance of reaction reagents, bromide and carbon were established with clear pathways and destinations by various analytical chemistry methods. The debromination process in functionalization significantly reduced the total toxicity by giving inorganic bromide and bisphenol A (BPA) as two main products. The results confirm this process to be an environmentally friendly process which can provide a basis for evaluating recycling processes.

1. Introduction

The rapid development of electrical and electronic equipments (EEE) manufacturing industry has lead a revolution on entertainment, communication, transportation and virtual payment. The anticipated increase in demand for electrical and electronic equipments from both industries and individuals experiencing a high rate of upgrading and shorten life span brings a global sustainability concern. This has given rise to the rapidly increasing amount of waste electrical and electronic equipments (WEEE) [1]. Currently, 50 million tons of WEEE is produced annually and the situation is getting even worse due to the increasing rate of WEEE which is reaching as high as around 5% per year [2]. Therefore, it is estimated that there will be 110 tons of WEEE globally in 2030 [3]. Among WEEE, the production of waste printed circuit board (WPCB), the core part of WEEE, stands out as the most difficult component to treat and most valuable part to recycle. Although it only counts for 3% by weight of the total amount of WEEE, it contributes the majority of the pollution due to the toxic substances inside it, including heavy metals, brominated flame retardant and plastics [4,5].

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Extensive studies on the field of WPCB treatment or recycling have been conducted and several techniques have been developed. Traditional treatment methods for WPCB include incineration and landfilling. However, co-landfilling of WPCB with municipal solid waste in landfill site causes serious leaching issues under acidic conditions [6–8]. Leachate, containing brominated organic compounds and heavy metals poisons the soil on landfill sites and neighboring environment and spreads rapidly though any aquatic system [9,10]. As for incineration, it is capable of achieving significant volume reduction (~50 wt%) and energy recovery. Nevertheless, incineration also generates severe environmental issues including gas pollutant emissions and highly toxic bottom ash requiring necessary treatment [11,12]. Moreover, during the incineration process, the decomposition of WPCB releases considerable amounts of heavy metals, volatile organic compounds (VOCs), polychlorinated dibenzo-p-dioxins/polychlorinated dibenzofurans (PCDD/Fs) and polybrominateddibenzo-p-dioxins and dibenzofurans (PBDD/Fs) [13–16]. These emissions bring about serious environmental concerns in the absence of post-treatment. Also, fly ash as well as bottom ash with high content of heavy metal still remains a problem for its treatment and thus require further treatment [12,17]. Therefore, the environmental issues related to WPCB landfilling and incineration raise public attention reflecting on these techniques. Therefore, recycling has been proposed as an option for WEEE treatment since it significantly cuts the emissions by reusing the waste material. Several techniques have been developed including pyrometallurgy, hydrometallurgy or biometallurgy recycling techniques to recover the valuable components inside WPCB [18–24]. However, the main focus of these recycling techniques is the metallic fraction (MF) inside WPCB. Thus these techniques are incapable to achieve full recovery since some hazardous materials are still emitted due to the deconstruction of the non-metallic fraction (NMF) of WPCB [25,26]. Recently, corona electrostatic separation has been used to separate the MF and NMF with high separation efficiency [27,28]. The MF with high purity is already a commercial entity for market sales. However, despite the fact that the MF has the purity that is high enough to enter the market, the NMF leftover still remains as a potential pollutant source due to the toxic substance it contains including bromoorganic compounds. Previously the majority of NMF ended up in landfill or incineration processes which caused environmental problems such as dioxin emissions or metal bearing leachate [29].

Recently, recycling NMF as virgin material or additive has been taken into consideration. Guo et al. have done a series of studies focusing on the application of NMF of WPCB as the alternative for wood flour in the production of phenolic moulding compounds (PMC) [30,31]. But the direct use of NMF is not capable to remedy the cost of the intensive energy input in the mechanical separation process. Therefore, the attempt to modify NMF as a novel carbon source in adsorbent preparation or electrochemistry applications for appreciation is indispensible [32,33]. Recently, Hadi et al. developed a process to recycle the NMF of WPCB as a highly efficient adsorbent to treat heavy metal contaminated wastewater [34-36]. It showed superior heavy metal uptake efficiency and added great value to the products.

Although extensive studies are being developed in NMF recycling and reusing, these techniques have rarely been analyzed and evaluated on their external emissions to give a whole picture of environmental impacts of the recycling process since they are all conducted in laboratory conditions and scale. Therefore, the material flow remains veiled for the majority of these works, indicating the disturbing fact that the threat of the emission due to the deconstructed part of non-recycling part of WPCB is covered by the limited value provided by the recycling products. The environmental and economical feasibility of these techniques stays controversial due to the incomplete emission analysis. Also, the threat of toxic substances like Br, HBr PCDD/Fs or PBDD/Fs have been underestimated or kept undiscussed in many studies [37–40]. In several works, there were neither emission analyses for bromide and carbon nor the establishment of any mass balance. Therefore, it is difficult to evaluate the total environmental impact of the whole process since some of the products including gas form Br_2, HBr or PCDD/Fs and PBDD/Fs, which are even more hazardous than WPCB [25,41]. Summarily, the missing of emission analysis is a potential threat to the environment and human health.

Hence, in this study, a systematic research study was conducted to analyze in detail the environmental emission impacts including gas, liquid and solid phases. Mass balances of reaction reagent, bromide as well as carbon were established by different analytical techniques. The mass balances with good recovery rate of different elements showed good environmental friendliness by converting highly toxic substances to low toxicity or harmless substances. The final products of the whole process are capable to be treated easily with minimal side effects to the environment. Also, the recycling performance of bromide for further use was investigated by adding an anion-exchange resin process.

2. Experimental

2.1. Material

The non-metallic fraction of WPCB (NMF) was collected from a local company with no further treatment. It is the powder product of a high efficiency corona electrostatic separator with the average size around a few hundred micrometers. The NMF possesses high hydrophobicity and low porosity which gives negligible ion-exchange ability as claimed in our previous work [42]. After a thermal-alkaline treatment process, the obtained material, named ANMF, was collected and stored in a desiccator for further characterization. Differently, ANMF is highly hydrophilic with excellent porosity, resulting high ion-exchange efficiency that endows it potential applications in adsorption, ion exchange and catalysis.

The surface characterization as well as the adsorption performance of both samples has been discussed in our previous work [34,43]. In this work, the composition of both materials were of interest thus the X-ray fluorescence (XRF) technique was conducted by a JEOL JSX-3201Z Element Analyzer and CHNS measurement (Vario EL III, Varian, Germany) and analysis was performed to determine the chemical composition of NMF and ANMF to set the foundation of mass balance.

2.2. Experimental setup

The emission analysis experiments were conducted in a laboratory scale horizontal quartz tubular reactor consisting of a gas inlet, a tubular furnace, a glass condenser, an impinger and an air bag assembled as shown in Fig. 1. Basically, approximately 0.56 g NMF was added into 20 mL 1 M potassium hydroxide solution to form a slurry mixture and then transferred to a quartz boat. The quartz boat was placed into the middle of the tubular furnace and then the whole system was sealed. Consequently, nitrogen as inlet gas with a rate of 20 mL/min was introduced into the furnace to purge air out and ensure an inert atmosphere. Afterwards, the temperature was increased to 250 °C with the ramping rate of 5 °C/min followed by a smoothly heating to 300 °C with the ramping rate of 2 °C/min. Then the temperature was kept at 300 °C for 1 h and cooled to room temperature. During the activation process, the non-condensable outlet gas was collected by a 5 L airbag after adsorption by an impinger with 100 mL 0.5 M potassium hydroxide solution. The activated sample and the quartz tube were washed by deionized water until the pH of surfactant is lower than