Chemical Engineering Journal 256 (2014) 415–420

Contents lists available at ScienceDirect

Chemical Engineering Journal

journal homepage: www.elsevier.com/locate/cej

Review

# Conversion of an aluminosilicate-based waste material to high-value efficient adsorbent

Pejman Hadi [a,b], Chao Ning [a], Weiyi Ouyang [a], Carol Sze Ki Lin [b], Chi-Wai Hui [a], Gordon McKay [a,c,*]

[a] Chemical and Biomolecular Engineering Department, Hong Kong University of Science and Technology, Clear Water Bay Road, Hong Kong Special Administrative Region
[b] School of Energy and Environment, City University of Hong Kong, Tat Chee Avenue, Kowloon, Hong Kong Special Administrative Region
[c] College of Science, Engineering and Technology, Hamad bin Khalifa University, Qatar

## HIGHLIGHTS

- A review on the applications of nonmetallic fraction (NMF) of waste printed circuit boards (PCBs).
- Examining the production and characterization of a novel adsorbent (A-NMF) from NMF.
- Study on the heavy metal removal efficiency of A-NMF in single- and multi-component systems.
- Best fit equilibrium isotherm modeling in single and binary component systems.

## ARTICLE INFO

*Article history:*
Received 2 May 2014
Received in revised form 2 July 2014
Accepted 3 July 2014
Available online 14 July 2014

*Keywords:*
Adsorbent production
Wastewater treatment
Waste printed circuit board
Waste recycling
Reclaimed nonmetallic fraction

## ABSTRACT

The recycling of waste printed circuit boards (PCBs) has become one of the global challenges in the technological era. The colossal volume of waste PCB generated annually coupled with its toxic nature and the existence of highly-precious metals in its composition intensifies the problems associated with waste PCB management and recycling. The two prevalent waste management options, landfill disposal and incineration, are being phased out for this special waste as a result of public health concerns. Hence, in the past few decades, several PCB recycling schemes are being introduced. The most efficient and environmentally-sound practice for waste PCB recycling has been the separation of metallic and nonmetallic fraction of PCBs by extensively-studied physico-mechanical approaches. Although the metallic fraction can be directly rendered into the market due to its high value, the nonmetallic fraction (NMF) is either disposed of in landfills causing secondary pollution or used as a low-value filler with the sole purpose of its safe disposal. This study presents a brief overview of the utilization of NMF as a filler in various industries. The main objective of the present review is to thoroughly examine the novel, highly efficient application of NMF as precursor for the production of a mesoporous structured adsorbent and its application in the removal of a myriad of heavy metals in single- and multi-component systems. In addition, the effects of the operational parameters on the adsorption behavior of the adsorbent material have been provided. Moreover, a comprehensive overview of the adsorption system modelling for single and binary-component systems for this novel material has been compiled.



## Contents



* Corresponding author at: Chemical and Biomolecular Engineering Department, Hong Kong University of Science and Technology, Clear Water Bay Road, Hong Kong Special Administrative Region. Tel.: +852 23588412; fax: +852 23580054.
*E-mail address:* kemckayg@ust.hk (G. McKay).

http://dx.doi.org/10.1016/j.cej.2014.07.017
1385-8947/

## 1. Introduction

E-waste has become one of the most intense challenges of the world in the last decade [1–4]. On account of the colossal quantity of e-waste generated annually throughout the world, significant programs have been inspired to decelerate the rate of the obsolescence of electronic devices [5–7]. However, these exercises have been hindered by the great desire of individuals to keep updated by the rapid technological breakthroughs occurring on an almost daily basis [8–10]. Also, the steadily-declining prices of electronic devices encourage the end-users to replace their gadgets more frequently [11,12]. Thus, it is estimated that the generation of e-waste will continue to increase at a fast and irresistible pace.

Traditionally, landfill disposal and incineration were the predominant methods for e-waste handling [4,9,10,13,14]. However, due to the existence of a myriad of toxic substances in e-waste, their well-recognized ecological impacts and augmented public concerns regarding their health and environmental impacts, these two methods are now being overshadowed by more recent efforts for environmentally-sound e-waste recycling techniques [14–17].

Printed circuit boards (PCBs), as the heart of any electronic equipment, poses one of the major challenges in e-waste recycling due to the presence of a variety of toxic components, such as heavy metals and brominated flame retardants, in their composition [18–20]. Separation of the metallic and nonmetallic fractions of waste PCBs by physico-mechanical approaches, such as corona electrostatic, eddy current, magnetic, gravity and density separation techniques, has been proved to be a promising environmentally-benign method to recycle the components [21–28]. These physico-mechanical methods have been comprehensively studied by Cui and Forssberg [29]. The reclaimed metallic fraction has received widespread attention both in industry and research because of the high value of the metals which can be returned to the market [30–36]. Nonetheless, a considerable amount of the nonmetallic fraction of the waste PCBs (NMF), typically comprising about 70 wt% of the PCBs, is either disposed of into landfills, causing secondary pollution and resource waste, or incinerated with the potential emissions of dioxins, furans and heavy metals [37–41].

In the past few years, a few applications have been introduced for the reclaimed NMF. Zheng et al. [38,42,43] proposed using silane-modified NMF as reinforcing filler in polypropylene composites. The aim of the study was to enhance the mechanical properties of the composite by incorporating this inorganic filler into the polymer matrix. They showed that the addition of NMF into the composite up to an optimum amount significantly enhanced its tensile and flexural properties due to the inherent properties of fiberglass. When the NMF content increased further, higher stress concentration points are induced leading to crack initiation, propagation of cracks along the weak interface, incapability of the filler to terminate the crack propagation, interfacial debonding and thus the reduction of flexural strength and modulus. Xu et al. [44] modified the NMF by pimelic acid and introduced it as filler into the polypropylene matrix. It was demonstrated that the mechanical properties of the composite were considerably enhanced when small amounts of pimelic acid was used, whereas high loading of pimelic acid resulted in the deterioration of the composite properties. It was theorized that the addition of pimelic acid- modified NMF gradually transformed the $\alpha$ crystals of the polymer to $\beta$ crystals. In contrast to polypropylene, using NMF in high density polyethylene (HDPE) significantly reduced the tensile strength, elongation at break and Izod impact strength of the composite [45]. Guo et al. [37,46] have suggested the partial replacement of wood flour, as filler in phenolic molding compounds with NMF. They showed that although the mechanical and thermal properties of the composite was enhanced at a certain NMF content, the flowability of the composite was decreased to a great extent which hindered the processing of the composite. The application of NMF in inorganic composites, such as asphalt and cement, has also been investigated [47–49]. The disadvantage of the NMF addition to the composite, namely difficulty in the flow of the composite, lower ductility of the asphalt composite and reduced compressive strength, flexural strength and tensile bond strength of the cement composite overshadowed the enhancement of the composite properties [47,48]. Several other similar applications have also been proposed [50–55].

It is believed that the application of NMF as low-value filler in various industries is aimed solely at the safe non-landfill disposal of NMF for environmental conservation, while the potential of this material to be utilized as precursor to produce high value-added materials has been neglected. This paper presents a comprehensive review on the utilization of reclaimed nonmetallic fraction of waste printed circuit boards (NMF) as a precursor for the preparation of high value adsorbent/ion exchanger for the removal of heavy metal ions from wastewater streams. The removal efficiency of this waste-derived material has been summarized for various heavy metals in single and multicomponent systems. The application of modified NMF as adsorbent has multi-advantages, namely environmental conservation, resource recovery and wastewater remediation.

## 2. Characterization of the virgin material (NMF)

The properties of the micron-size non-metallic fraction of waste printed circuit boards (NMF) has been thoroughly characterized by several techniques including nitrogen adsorption–desorption, Fourier transform infrared spectroscopy (FTIR), X-ray fluorescence (XRF) and X-ray photoelectron spectroscopy (XPS). The in-depth understanding of the NMF composition was considered as one of the major contributions by Hadi et al. [56]. The elemental analysis results indicated that NMF consisted of around 21 wt% carbon and the rest of the composition of this material is non-carbon which was elucidated by XRF technique. The XRF results revealed that the dominant constituents of this waste material are aluminum, silicon and calcium which was believed to originate from calcium aluminosilicate. Due to the presence of carbon and aluminosilicate, they hypothesized the potential of this material to function as an adsorbent. However, further analysis showed that NMF has a trivial surface area (<1 $m^2/g$) with almost no active functional group on the surface [56].

## 3. Activation hypothesis

Hadi et al. [57] hypothesized that the cleavage of the unreactive siloxane bonds not only results in the creation of active silanol