



Using an integrated decontamination technique to remove VOCs and attenuate health risks from an e-waste dismantling workshop



Ranran Liu ^{a,c,1}, Jiangyao Chen ^{a,b,1}, Guiying Li ^{a,b}, Taicheng An ^{a,b,*}

^a State Key Laboratory of Organic Geochemistry and Guangdong Key Laboratory of Environmental Protection and Resources Utilization, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou 510640, China

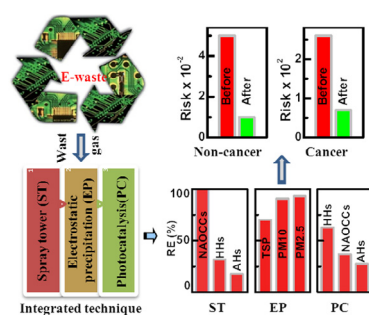
^b Institute of Environmental Health and Pollution Control and School of Environmental Science and Engineering, Guangdong University of Technology, Guangzhou 510006, China

^c University of Chinese Academy of Sciences, Beijing 100049, China

HIGHLIGHTS

- Pilot-scale removal of VOCs was carried out during electronic waste dismantling.
- Water-soluble VOCs and particles were pretreated before photocatalysis.
- Photocatalysis prefers degradation of VOCs with higher dielectric constant.
- Integrated reactor show high and stable removal ability to emitted VOCs.
- Health risks of individual and total VOCs decrease significantly after treatment.

GRAPHICAL ABSTRACT



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ABSTRACT

Recycling e-waste is increasingly recognized as an important resource management strategy; however, the process emits different pollutants, including volatile organic compounds (VOCs). Sixteen dominant VOCs, with total concentrations ranging from 1.6×10^3 to $6.7 \times 10^3 \mu\text{g m}^{-3}$, were presented during the manual process of dismantling television printed circuit boards using electric heating furnaces. An integrated treatment technique, involving a spray tower (ST), electrostatic precipitation (EP), and photocatalysis (PC), was used to eliminate these VOCs. The highest VOC removal efficiency during the 60-day treatment period was 69.5%. The removal efficiency was mainly due to the combined effect of preferential elimination of hydrosoluble VOCs and efficient interception of large-sized particles by ST; the enhanced capture efficiency of micro-sized particles by EP; and the dominant degradation of particle-free VOCs by PC. The PC treatment was able to remove more hydrocarbons (an average 62.7%) than nitrogen- and oxygen-containing and aromatic compounds (36.4% and 27.3% in average), due to the hydrocarbons' higher dielectric constants. Risk assessment revealed that the non-cancer and cancer risks associated with VOCs significantly decreased after the integrated technique was applied, indicating that the treatment is an efficient approach for purifying the atmosphere and protecting human health inside e-waste recycling workshops.

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* Corresponding author at: State Key Laboratory of Organic Geochemistry and Guangdong Key Laboratory of Environmental Protection and Resources Utilization, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou 510640, China

E-mail address: antc99@gig.ac.cn (T. An).

¹ Both authors contributed equally to this work and were considered as co-first authors.

1. Introduction

Increasing population growth and rapid industrialization have placed enormous pressure on traditional raw material sources and have produced large volumes of electronic waste (e-waste) [1,2]. A win-win situation for communities, governments, recyclers, and the environment can occur when e-waste is properly recycled, because e-waste recycling is an important form of resource recovery [3,4]. When the e-waste recycling process is not sufficiently regulated, large amounts of gaseous pollutants are emitted and released into air, severely polluting the atmosphere and threatening human health [5].

During e-waste dismantling processes, heavy metals and organic pollutants have been demonstrated as the main pollutants [6,7]. Generally, significant researches have been focused on the pollution profiles of heavy metals and semi-volatile organic compounds (SVOCs) in e-waste recycling environments [8–10]. There has been limited research, however, about contamination from volatile organic compounds (VOCs) from e-waste recycling, especially inside workshops [11]. These VOCs could pose health risks for workers, due to a lack of efficient environmental protection equipment in these workshops [12,13]. As such, efficient VOCs purification technologies are needed to mitigate health risks in these facilities.

As a first example of such a technology, photocatalysis (PC) has attracted considerable attention based on its ability to effectively degrade organic pollutants; this ability is driven by the generation of powerful and non-selective oxidant active species [14–16]. PC has been demonstrated to effectively degrade more than sixty kinds of individual VOCs [17–22], as well as mixed VOCs in laboratory settings [23,24]. However, unlike in lab environments, complex real-life situations can deactivate catalysts, primarily because of coexisting particulate matter in real waste gas treatment [25]. Therefore, to maintain the high efficiency and stability of PC technique, particle removal technologies must be sequenced properly.

Turning to a second kind of technology, previous studies have indicated [26,27] that electrostatic precipitation (EP) efficiently removes ultra-fine particles (e.g., micro- and nano-meter in size) from industrial waste gas. Recent work showed that total suspended particulates can be effectively trapped by the electrostatic precipitator, enhancing the ability of a subsequent PC system to remove VOCs at an on-site e-waste recycling workshop. Besides ultra-fine particles, particles with larger sizes (such as dust on aged e-waste surfaces) must be eliminated before reaching the EP unit. This is because larger particles could damage the EP unit's discharge electrodes, decreasing the EP unit's efficiency in removing ultra-fine particles.

A third technology is the spray tower (ST), which has emerged as a widely used and easily constructed and operated control device to remove different sized particles from industrial effluent gases [28,29]. This technology also removes some water-soluble atmospheric pollutants [30]. After this pretreatment, the PC reactor can then degrade and detoxify particle-free gaseous organics [19,31].

In this study, an integrated ST-EP-PC technique was applied to assess VOC elimination and risk reduction inside a waste printed circuit board (WPCB) recycling workshop, on a pilot scale. The abilities of ST, EP, and PC technologies to remove particles and VOCs were analyzed separately; the integrated technique was then evaluated for its ability to successfully eliminate atmospheric VOCs. Following this, the potential health risk from different VOCs was evaluated before and after the 60-day treatment operation. The goal of the study was to provide useful guidance for controlling VOC emissions from WPCB recycling processes.

2. Experimental design

2.1. Study site

The pilot scale experiments were conducted in a WPCB recycling workshop in Guangdong Province, China, where the WPCBs of television are manually recycled on electric heating furnaces (EHFs). The experiments lasted for 60 days, from November 2014 to January 2015.

2.2. Set-up

A pilot-scale integrated ST-EP-PC reactor (Fig. S1) was constructed to purify waste gas emissions. The waste gas was first fed into the ST unit (approximately 4500 mm high with a 3000 mm diameter), and then into the EP-PC integrated unit (2260 mm × 2500 mm × 3590 mm). Gas was fed using two centrifugal pumps mounted separately between the ST outlet, and the PC outlet to obtain a stable flow-rate of 10,000 m³ h⁻¹. Waste gas was introduced into the ST reactor from the bottom to top with residence time of 2.0 s and fed into the EP-PC integrated unit with the residence time of 7.3 s.

The ST unit mainly consists of a polypropylene ST and a water spraying and circulating unit (with a rate of 0.4 m³ h⁻¹). The former portion was divided into three equal-height layers, each packed with commercial rasching rings (12 mm × 12 mm × 3 mm; Bulk density: 0.69–0.73 g cm⁻³; S_{BET}: 0.42–0.48 m² g⁻¹; porosity ≥ 70%).

For the EP system, 16 electrostatic dust collectors were distributed symmetrically at the bottom of the EP-PC integrated reactor. The upper part of the reactor was divided into ten equal units using 20 pieces of foam nickel (1000 mm × 500 mm for each) coated TiO₂ (commercial Degussa P25; particle diameter: 300 nm; specific surface area: 50 m² g⁻¹) and 44 vacuum ultraviolet lamps (30 W for each, maximum wavelength at 254 nm with a minimum <5% emission at 185 nm, ZY30S19 W, Guangdong Cnlight CO. Ltd., China). Details about the EP and PC units are provided in Supporting Information and previous papers [13,25].

2.3. Sample collection and analysis

VOC samples were collected at the inlet, ST outlet, and PC outlet, using 2.7-L stainless Summa canisters (ENTECH Instruments Inc, Silonite™), about every 10 days. The 10, 20, 30, 40, and 50-day samples were denoted as 1st, 2nd, 3rd, 4th, and 5th samples, respectively. Canisters were pre-cleaned five times with ultra-high-purity nitrogen, and then pre-evacuated before sampling. VOC analyses were conducted using an Entech 7100 pre-concentrator (Entech Instruments Inc., CA, USA), followed by gas chromatography–mass spectrometry (7890-5975 GC–MS, Agilent technologies, USA), using the U.S. Environmental Protection Agency (USEPA) TO-15 method [32]. The column was 60 m × 0.32 mm with 0.25 μm thick film (DB-5MS, Agilent Technology, USA).

Waste gas from the Summa canisters were highly concentrated by the pre-concentrator and swept into the column for separation after quickly desorbed at 120 °C min⁻¹. The oven temperature was programmed as follows: the initial temperature of 40 °C was held for 5 min; the temperature was then increased to 150 °C at a rate of 5 °C per min; the temperature was then raised to 250 °C at a rate of 15 °C per min, and was then held for another 2 min. The temperature of the injector, transfer line and detector were: 200 °C, 290 °C and 230 °C, respectively. Ultra-high-purity helium was used as the carrier gas, at a constant flow of 1.2 mL per min; the MS was

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