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Co-gasification of sewage sludge and woody biomass in a fixed-bed downdraft gasifier: Toxicity assessment of solid residues

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ABSTRACT

As the demand for fossil fuels and biofuels increases, the volume of ash generated will correspondingly increase. Even though ash disposal is now strictly regulated in many countries, the increasing volume of ash puts pressure on landfill sites with regard to cost, capacity and maintenance. In addition, the probability of environmental pollution from leakage of bottom ash leachate also increases. The main aim of this research is to investigate the toxicity of bottom ash, which is an unavoidable solid residue arising from biomass gasification, on human cells *in vitro*. Two human cell lines i.e. HepG2 (liver cell) and MRC-5 (lung fibroblast) were used to study the toxicity of the bottom ash as the toxins in the bottom ash may enter blood circulation by drinking the contaminated water or eating the food grown in bottom ash-contaminated water/soil and the toxic compounds may be carried all over the human body including to important organs such as lung, liver, kidney, and heart. It was found that the bottom ash extract has a high basicity (pH = 9.8–12.2) and a high ionic strength, due to the presence of alkali and alkaline earth metals e.g. K, Na, Ca and Mg. Moreover, it also contains concentrations of heavy metals (e.g. Zn, Co, Cu, Fe, Mn, Ni and Mo) and non-toxic organic compounds. Although human beings require these trace elements, excessive levels can be damaging to the body. From the analyses of cell viability (using MTS assay) and morphology (using fluorescence microscope), the high toxicity of the gasification bottom ash extract could be related to effects of high ionic strength, heavy metals or a combination of these two effects. Therefore, our results suggest that the improper disposal of the bottom ash wastes arising from gasification can create potential risks to human health and, thus, it has become a matter of urgency to find alternative options for the disposal of bottom ash wastes.

1. Introduction

Thermal processes such as incineration and gasification can be considered as sustainable technology which is mostly used for the solid waste treatment. It is sustainable both in terms of waste volume reduction and a source of renewable energy. However, burning of solid waste in incinerators leads to serious negative environmental and human health effects, due to emission of massive amount of toxic gases (Beylot and Villeneuve, 2013; Roy et al., 2011) resulting from the complete combustion process inside the incinerators. Gasification is a process that slowly converts large molecules of organic or fossil based carbonaceous materials into smaller molecular and finally, into gaseous product which mainly consists of carbon monoxide, hydrogen and carbon dioxide (Ruiz et al., 2013; Simone et al., 2012). This is achieved by chemically reacting carbonaceous materials at high temperatures (>700 °C) with a controlled amount of oxygen and/or steam to avoid complete combustion (Samolada and Zabaniotou, 2014; Zhang et al., 2013). Therefore, gasification not only provides a cost-effective and environmental friendly way of discharging solid waste, but also produces syngas as a clean energy fuel, offering an alternative clean process for recovering energy from the waste.

Apart from the gaseous product, gasification also generates solid residues as unavoidable by-products, which amounts varying from 10% to 30% of the original feedstock mass, depending on efficiency of the gasifier and feedstock materials (Sabbas et al., 2003; Belgiorno et al., 2003). Depending on the carbon content of the

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residue, it can be classified as char (unreformed carbon) or bottom ash (primarily minerals and metals with minimal carbon). Char is usually re-introduced into the gasifier to generate more energy. On the other hand, bottom ash is generally disposed in landfills (Travar et al., 2009) or re-utilized as a filling material for construction applications (Forteza et al., 2004). Although bottom ash is classified as nonhazardous waste, fresh bottom ash contains various inorganic compounds, consisting mainly of oxides, hydroxides and alkali salts, which cause a high pH value of the bottom ash (Rocca et al., 2012) and trace amounts of heavy metals. Moreover, the fresh bottom ash may also contain organic compounds arising from incomplete combustion of solid wastes (Liu et al., 2008). As a result, the fresh bottom ash arising from solid waste gasification can have toxic properties related to trace elements, organic contaminants and alkalinity, or a combination of these factors. The improper disposal of bottom ash wastes may cause all types of pollution i.e. air, soil, and water (Sivula et al. 2012a; Sivula et al. 2012b; Liu et al. 2008).

As the demand for bioenergy production increases, ash and residue volumes will increase. Even though the ash disposal is now strictly regulated in many countries, the rapid increase of ash results in the high pressure on landfill sites regarding cost, capacity and maintenance. Moreover, ash leachate may leak or spill from the landfill sites. For example, in the Kingston Fossil Plant (Tennessee, USA) spill in 2008, 1.1 billion gallons (4,200,000 m^3) of fly ash slurry was spilled from an on-site landfill, covering more than 300 acres of surrounding land and water (Dewan, 2008). Therefore, the chance of environmental pollution by ash leachate is ever increasing. The ash contaminants can accumulate inside plants and animals, which can harm or kill them.

Up to date the effect of emissions from the gasification of solid wastes such as sewage sludge on the human health has seldom been addressed (Kabir and Kumar, 2012; Pa et al. 2011), especially with regard to the effect of solid residues, because their effect may last for a long period, such as 100–1000 years. However, it is quite difficult to draw firm conclusions on human toxicity, because even the best emissions data is incomplete and the true impacts of most chemicals and mixtures of chemicals are poorly understood.

From those points of view, the main purpose of this work is to investigate the toxicity of bottom ash arising from biomass and/or solid waste gasification. The main reason is that the bottom ash arising from gasification is usually disposed in the landfills, and the leaching of toxic compounds by rain or surface water can cause severe pollution to environment and possibly endanger human health. By drinking the contaminated water or eating the food grown in bottom ash-contaminated water/soil, toxic compounds may be carried all over the human body to important organs such as the lung, liver, kidney and heart. Moreover, understanding of toxic properties of bottom ash wastes generated from gasification is necessary for establishing environmentally and economically benign solid wastes management. In this work, the extracts from the bottom ashes arising from gasification processes of (i) pure woodchip (which is represented by PWG in the following) and (ii) 20 wt.% sewage sludge and 80 wt.% woodchips (which is represented by 20SWCG in the following) (all samples were collected from our present work) were characterized by determination of elements (i.e. heavy metals, alkaline earth metals and alkali metals), polycyclic aromatic hydrocarbons (PAHs) and other organic compounds concentrations. Two types of human cell lines, i.e. HepG2 (liver cell) and MRC-5 (lung cell), were used to examine toxicity of the bottom ash leachates. The liver cell line, HepG2 was selected as it possesses a number of characteristic enzyme pathways of human hepatocytes and is regarded as a "gold standard" in toxicology (Kang et al. 2010; Babich et al. 1988). MRC 5 lung fibroblasts were chosen as the lungs are major organs in the respiratory system and as a large volume of blood passes through the pulmonary circulation, toxic substances which may exert deleterious effects are easily conveyed to the lungs. The viability and morphology of HepG2 and MRC-5 cells were used to analyze the toxic effects on those human cells.

2. Materials and methods

2.1. Collection of sewage sludge and bottom ash samples from gasification

Sewage sludge samples were obtained from the Ulu Pandan Water Reclamation Plant, under the Public Utilities Board (PUB), the National Water Agency of Singapore. The sewage sludge sample from different batches was mixed, dried and ground into powders. In the present study, woody biomass with an average length of 35 mm, width of 10 mm, and thickness of 2.5 mm or its mixture with the above sewage sludge sample was used as the feedstock for gasification in a 10 kW fixed bed downdraft gasifier (from All Power Labs, USA). The air flow rate investigated was from 4.0 to 10.0 L/s. The temperatures in pyrolysis and reduction zones were 550–800 °C and 650–900 °C, respectively. The main processes taking place in this downdraft gasifier can be described as follows:

- Drying – removal of moisture from the feedstock

$$\text{Biomass}_{(wet)} + \text{heat} \rightarrow \text{Biomass}_{(dry)} + H_2O(g)$$

- Pyrolysis – thermal breakdown the feedstock into tar and charcoal

$$\text{Biomass}_{(dry)} + \text{heat} \rightarrow C_{charcoal} + \text{tar}$$

- Combustion and tar cracking – burning of charcoal and tar to provide heat for the rest of the processes and the thermal cracking of a portion of the tar into CO and H_2 (syngas).

$$C_{charcoal}, \text{tar} + O_2(\text{from air}) \rightarrow CO_2(g) + H_2O(g) + \text{heat}$$

$$\text{tar} + \text{heat} \rightarrow CO + H_2$$

- Reduction – reaction of combustion products and charcoal to produce syngas.

$$CO_2 + C_{charcoal} + \text{heat} \rightarrow 2CO$$

$$H_2O + C_{charcoal} + \text{heat} \rightarrow CO + H_2$$

Within the gasifier the feedstock flowed downwards by gravity and air as a gasifying (or oxidizing) gas was introduced into the combustion zone of the reactor. Bottom ash samples were collected from the ash pit at the bottom of the fixed bed downdraft gasifier after the gasification of pure woodchip (PWG) and 20% sludge and 80% woodchip (20SWCG). However, due to the structure of the gasifier, some small char particles formed in the reduction zone may fall into the ash pit and subsequently be mixed with the bottom ash. As char can be recycled rather than landfilled in actual gasification processes, they were removed via sieving before the toxicity test.

2.2. Extraction of soluble toxic substances from samples

Fig. 1 shows the process for solute extraction and toxicity test. 8 g of sample of either sewage sludge or sieved bottom ash was weighed and placed in a 50 mL tube, and mixed with 40 mL of deionized (DI) water, resulting in a liquid-to-solid (L/S) ratio of 5.0. The mixture was then vortexed for 5 min, followed by overnight static leaching for 12 h, and centrifuged at 15,000 rpm for 10 min. The supernatant was transferred into a separate tube and