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Leachates of municipal solid waste incineration bottom ash from Macao: Heavy metal concentrations and genotoxicity

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Abstract

Heavy metals in municipal solid waste incineration bottom ash (MSWIBA) may leach into soil and groundwater and pose long-term risks to the environment. In this study, toxicity characteristic leaching procedure (TCLP) was carried out on the MSWIBA from Macao. Heavy metals in leachates were determined by inductively coupled plasma mass spectrometry (ICP-MS) and inductively coupled plasma atomic emission spectrometry (ICP-AES), and genotoxicity of leachates was also evaluated by micronucleus (MN) assay with *Vicia faba* root tip cells. The results showed that the concentrations of aluminium (Al), manganese (Mn), cobalt (Co), cadmium (Cd) and mercury (Hg) in the leachates were less than 0.01 mg l^{-1}, and those of iron (Fe), copper (Cu) and molybdenum (Mo) were less than 0.1 mg l^{-1}. The concentrations of chromium (Cr), zinc (Zn), selemium (Se), strontium (Sr), barium (Ba) and caesium (Cs) were between 0.11 mg l^{-1} and 2.19 mg l^{-1}. Lead (Pb) concentrations, in particular, reached as high as 19.6 mg l^{-1}, significantly exceeding the maximum concentration limit (5 mg l^{-1} for lead by TCLP). Compared with the negative group, a significant increase of MN frequencies was observed in the leachate-exposed groups ($P < 0.05$). With the increase of heavy metals in the leachates, the toxic effects on the *Vicia faba* root tip cells increased, implying that heavy metals were the main factors causing the genotoxic effects. Our results suggested that apart from chemical analysis, bioassays like the MN assay of *Vicia faba* root tip cells should also be included in a battery of tests to assess the eco-environmental risks of bottom ashes before decisions can be made on the utilization, treatment or disposal.

Keywords: Municipal solid waste incineration bottom ash (MSWIBA); Toxicity characteristic leaching procedure (TCLP); Heavy metal; Genotoxicity; Micronucleus (MN) assay

1. Introduction

Incineration, which aims to reduce the volume, the toxicity and the reactivity of the waste (Klein et al., 2001), is a viable management strategy throughout the world for treating the increasing combustible municipal solid waste (MSW) that cannot be recycled (Eighmy et al., 1995; Ferreira et al., 2003). Although incineration reduces greatly the volume (by about 90%), the mass (by about 75%) of MSW and provides energy (Chimenos et al., 1999), it is not the final solution of managing MSW (Ferreira et al., 2003). Since the solid residues (bottom ashes (BA), fly ashes) it generates still amount to roughly 17 Mt per year world-wide, which must subsequently be disposed of in an environmentally acceptable manner (Chimenos et al., 1999; Klein et al., 2001). This amount is expected to double within the next 10 or 15 years (Chimenos et al., 1999; Klein et al., 2001). Moreover, the advance of air pollution control measures in municipal solid waste incineration (MSWI) has resulted in a shift of constituents of concern from air emissions to the solid

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residues (Sawell et al., 1995; van der Sloot et al., 2001). Heavy metals (after undergoing gasification, oxidation, chlorination, condensation, coagulation, and nucleation), which come from raw wastes, are condensed into incinerated residues and thus may pose a threat to the environment (Gau and Jeng, 1998). During MSWI, lithophilic metals such as Fe, Cu, Cr, and Al remained mainly in the BA while Cd volatilized and condensed to the fly ash. About two thirds of Pb and Zn was found in the BA despite their high volatility (Jung et al., 2004). BA, which is the object of this study, represents about 80% of the residues and contains various substances that may pose a threat to the environment (Klein et al., 2001). The evaluation of the environmental quality of such residues is necessary before decisions can be taken on the utilization, treatment or disposal of them (van der Sloot et al., 2001).

In the last decade, most of studies focus on the chemical composition, mineralogical characteristics, and heavy metals leaching behaviors of MSWIBA (Eighmy et al., 1995; Gau and Jeng, 1998; Chimenos et al., 1999; Chang et al., 2001; van der Sloot et al., 2001; Bruder-Hubscher et al., 2002; Chimenos et al., 2003), fewer studies have addressed the issue of its (eco)toxicological consequences (Schramm et al., 1999; Radetski et al., 2004). Although in the past the analytical techniques improved rapidly, there is a huge lack in the quantitative evaluation of the risk of a mixture of compounds (such as BA) determined by physical-chemical analytical techniques (Schramm et al., 1999). Therefore, a complemental bioassay strategy should be developed with a focus on the most important (eco)toxicological effects. The biological endpoints are chosen according to their importance of known biological targets. Genotoxicity and/or disruption of the genome are ones of the first targets of concern (Schramm et al., 1999). Micronucleus (MN) assay in *Vicia faba* root cells, which were validated and its protocol were standardized through a program under the International Program on Chemical Safety, is highly sensitive and capable of detecting mutagens, clastogens and carcinogens from the environment, and showed excellent correlations with tests in the mammalian systems and human lymphocytes systems (Grant, 1994; Ma, 1999). It has been recommended for use in mutation screening or monitoring by the Royal Swedish Academy of Sciences, Committee 17 of the Environmental Mutagen Society and the World Health Organization (Grant, 1994).

Macao is a small island less than 27.3 km^2, yet has more than 0.46 million inhabitants. In additional to this high population density, accelerated economic development and enhanced living standards in the last decade have led to the generation of more MSW with a more complex composition. Today, incineration is a major approach in Macao for managing the increasing production of MSW. Landfilling is the main management option for the MSWIBA in Macao, as in many countries and territories (Ibanez et al., 2000; Klein et al., 2001; Ferreira et al., 2003). The potential pollution risks of the BA are of wide concern.

At present, the available (eco)toxicological data on the MSWIBA are relatively scarce. Moreover, the mineralogical characteristics and the chemical composition of MSWIBA varied either in different areas or during different periods. Thus, putting the extrapolation of published results to the MSWIBA from Macao is under question.

In the present study, toxicity characteristic leaching procedure (TCLP) suggested by the USA Environmental Pollution Agency (EPA) has been carried out on the MSWIBA from Macao. The Inductively Coupled Plasma Mass Spectrometry (ICP-MS) and Inductively Coupled Plasma Atomic Emission Spectrometry (ICP-AES) were employed to determine the contents of heavy metals in the leachates. The genotoxicity of the leachates was screened by MN assay in *Vicia faba* root cells. The aim is to provide data on its potential risks on the environment, and to provide policy maker with better information for planning of sound environmental actions and control measures.

2. Materials and methods

2.1. Sampling of bottom ash

Samples of MSWIBA were provided by Macao EPA. The sampling of MSWIBA was carried out in accordance with the recommendations of the International Ash Working Group (IAWG, 1997). Homogeneous steps were applied to the materials in order to derive representative laboratory samples to be used for the following experiments.

2.2. Leaching extraction procedure

The leaching extraction procedure followed the USA EPA Method # of 1311 with minor modifications (EPA., 1990). Triplicate BA samples were leached by three different extraction fluids respectively, which were deionized water (A) and two acetic extractants (B: pH 4.9, and C: pH 2.9). Since the average precipitation of a year was about 1869.4 mm in Macao in last century (SMG, 2000), the BA in the landfills will be leached by relatively more rain. The liquid-to-solid ratio was enlarged to 40:1, following an agitation extraction with a speed of 30 rpm for 20 h. Leachates were collected and filtered through a 0.45-μm membrane filter (Millipore). Each leachate was immediately prepared for metal elements analysis and MN assay in *Vicia faba* root cells, respectively.

2.3. Analysis of metal elements

The metal elements leached were determined by Perkin Elmer Elan 6000 ICP-MS and Varian Vista ICP-AES in the Laboratory of Isotope Geochronology and Geochemistry, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, with external standard calibrations (Wei et al., 2003a; Wei et al., 2003b). Analytical precision was better than 5% for the metal elements except Cd and Mo