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Heavy metal immobilization and microbial community abundance by vegetable waste and pine cone biochar of agricultural soils

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HIGHLIGHTS

- Vegetable waste and/or pine cone biochars immobilized Pb in soils.
- Vegetable waste biochars were most efficient in Pb immobilization.
- Torrefied biomass at 200 °C was most beneficial for soil microbial properties.
- Vegetable waste biochars were most efficient in improving soil chemical properties.
- Biochars were not effective for As immobilization in soils.

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ABSTRACT

In order to determine the efficacy of vegetable waste and pine cone biochar for immobilization of metal/metalloid (lead and arsenic) and abundance of microbial community in different agricultural soils, we applied the biochar produced at two different temperatures to two contaminated soils. Biochar was produced by vegetable waste, pine cone, and their mixture (1:1 ww^{-1}) at 200 °C (torrefied biomass) and 500 °C (biochar). Contaminated soils were incubated with 5% (ww^{-1}) torrefied biomass or biochar. Sequential extraction, thermodynamic modeling, and scanning electron microscopy equipped with energy-dispersive X-ray spectroscopy were used to evaluate the metal immobilization. Microbial communities were characterized by microbial fatty acid profiles and microbial activity was assessed by dehydrogenase activity. Vegetable waste and the mixture of vegetable waste and pine cone biochar exhibited greater ability for Pb immobilization than pine cone biochar and three torrefied biomass, and vegetable waste biochar was found to be most effective. However, torrefied biomass was most effective in increasing both microbial community and dehydrogenase activity. This study confirms that vegetable waste could be a vital biomass to produce biochar to immobilize Pb, and increase the microbial communities and enzyme activity in soils. Biomass and pyrolytic temperature were not found to be effective in the immobilization of As in this study.

1. Introduction

About 30–40% of annual world food production is wasted in the food supply chain for human consumption and vegetable waste is one of its main components. Mechanical damage during harvesting, and deterioration and damage during handling, storage and transportation contribute to the generation of large amounts of

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vegetable waste both in developing and developed countries. In the Asia-Pacific region, around 42% of vegetables and fruits go to waste (Gustavsson et al., 2011). About 3640 tons of food waste is generated per day in Hong Kong (Hk, 2015; Yu et al., 2016), and 13,000 tons per day in Korea (Kim et al., 2014). Vegetable waste is one of the main components of the food waste in Korea due to the high production and consumption rates of vegetables. Korea started to separate the collection of food wastes from other wastes in 1995. Landfills and oceans were used as disposal sites until banned in 2005 and 2012, respectively, due to the environmental problems and international regulations (i.e., London dumping convention) (Ju et al., 2016; Lee et al., 2009). Nowadays, composting, animal feed processing, biogas production, and incineration are commonly practiced in Korea to manage the daily accumulation of vast amount of food wastes (Kim et al., 2014; Ju et al., 2016). However, environment pollution by wastewater and toxic gases (e.g. methane, dioxin) continues to be a problem in Korea (Kim et al., 2014).

Biochar production is considered to be a feasible recycling method to reduce environmental problems created by food wastes in the world. Biochar is a carbon-rich byproduct of biomass pyrolysis at relatively low temperatures (<700 °C) and controlled atmospheric conditions (Hans-Peter Schmidt, 2012; Lehmann and Joseph, 2015). The biomass and pyrolytic conditions (temperature, heating rate, holding time, and gas reagents) are the important factors for determining the physico-chemical properties of biochar (e.g., surface area, surface functional groups, pH, and structural arrangements of carbon) (Ahmad et al., 2014a; Almaroai et al., 2014; Fang et al., 2016). Biochar has exhibited promising results in many environmental friendly applications including the heavy metals (HMs) immobilization in diverse range of soils with different physicochemical properties (Fang et al., 2016; Ahmad et al., 2016a; Inyang et al., 2016; Rajapaksha et al., 2016).

Agricultural soils worldwide reveal often high levels of HMs primarily due to anthropogenic activities (Bolan et al., 2014). The HMs in agricultural soils can be translocated to food crops and cause serious concerns associated with food safety (Shaheen and Rinklebe, 2015), and they can undergo several transformations, which are highly contingent on the biochemical and physical conditions, including soil pH, redox potential (Eh), soil texture, organic matter (OM) content, mineralogy, and microbial activities (Rupp et al., 2010; Shaheen et al., 2013). Consequently, the bioavailability of these HMs depends on the total HMs content, the stability of geochemical fractions, and dynamic soil biochemical properties. The bioavailable fractions of HMs carry major risks for safe crop production and human health (Ahmad et al., 2014b; Rinklebe et al., 2016), and they can be altered by dynamic soil biochemical reactions (Bolan et al., 2014; Frohne et al., 2011). Biochar application has been extensively reported as a vital amendment to immobilize the bioavailable fractions of HMs (Ahmad et al., 2014b, 2016a). However, there is still a lack of knowledge on microbial community and activity improvements by the immobilization of HMs by biochar applications.

High levels of HMs contamination in soils generally reduce the soil microbial communities and hence the balanced geochemical processes mediated by the microbial community (Bååth, 1989; Giller et al., 2009). While some HMs such as Cu, Co, Fe, Mn, Ni, and Zn are essential for cell regulation and production of certain enzymes, excessive amounts of HMs lead to detrimental conditions such as toxicity to metabolic reactions, enzyme production, and protective gene expressions (antibiotic resistance, soil-borne pathogen, etc.), except for virulent species (Bååth, 1989; Azarbad et al., 2015). Parelho et al., 2016 reported a reduction in microbial biomass carbon (MBC) and soil basal respiration due to the long-term exposure to As, Cd, Cr, Cu, Li, Ni, Pb, V, and Zn in contaminated soils. The stress for microorganisms caused by high levels of Cd, Mn, Cu, Pb, Ni, and Zn was reduced by the application of pyrogenic carbonaceous materials, pig manure, pig slurry, and marble waste. This resulted in an increased amount of soil bacteria and fungi in mine soils (Zornoza et al., 2016). Valentim dos Santos et al. (2016) found negative correlations between the soil enzyme activities of β-glycosidase, acid phosphatase, and urease, and the content of Zn, Pb and Cd in soil. The reductions of beneficial microbial species cause eventual weakening of geochemical processes, including decomposition and nutrient transformations (Parab et al., 2015).

This study aims to examine the applicability of vegetable waste as biomass to produce biochar to immobilize HMs in contaminated agricultural soils for an environmental friendly waste recycling. Pine cone (a local yard waste) was also used as biomass for biochar production for comparison with vegetable waste. The objectives of this study are to analyze: 1) the capacity of immobilization of HMs in contaminated soils with biochar produced at 200 °C (torrefied biomass) and 500 °C (biochar) from vegetable waste and pine cone, 2) the changes of soil chemical properties in biochar and torrefied biomass amended to HMs-contaminated soils, 3) the microbial community abundance and activity in biochar and torrefied biomass amended to HMs-contaminated soils, and 4) mechanistic evidence of the roles of biochar and torrefied biomass produced from vegetable waste and pine cone in HMs immobilization and soil quality improvement (i.e., chemical and microbial properties). Sequential extraction procedure was applied to determine the geochemical fractions of HMs in the soils after incubation with biochar and torrefied biomass, while fatty acid methyl ester (FAME) analysis and dehydrogenase activity (DHA) were employed to determine the microbial community and quantify the microbial activity.

2. Materials and methods

2.1. Soil collection and characterization

Soils were collected from two agricultural fields; a rice paddy (soil-RP) and an upland fallowed field (soil-UA) adjacent to historical mining areas of Seosung mine in Seosan-si and the Tancheon mine in Gongju-si located in the province of Chungcheongnam-do, Korea. Soil samples were randomly collected at a depth of 0–40 cm (25 random samples per field), and a composite sample was obtained by mixing all 25 samples (see Appendix A for more information). Samples were collected from the paddy field after the harvest. Soils were sieved through a 2 mm sieve, homogenized, and air-dried after removing all visible roots and fresh litter materials before the incubation experiment and physico-chemical analyses. See Appendix A for soil characterization. Both soils were highly contaminated with As and Pb and exceeded the soil contamination warning limits of Korea (Ministry of Environment, 2016) (Table 1).

2.2. Biochar production

Vegetable waste and pine cone were used to produce biochars and were collected from a local grocery market and from Kangwon National University (KNU) in Chuncheon in Korea, respectively. After removing a considerable amount of moisture by drying them in a greenhouse, vegetable waste was further dried in an electric oven at 50 °C until its weight was constant. Then it was separated into the individual components (Table A1). The waste material was mainly composed of sweet potato, leafy vegetables, and onions with percentages of 26.60%, 22.55%, and 18.48%, respectively.

The dried biomass was ground and screened through a 2 mm sieve. Vegetable waste, pine cone, and their homogenized mixture