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Research article

Potential application of gasification to recycle food waste and rehabilitate acidic soil from secondary forests on degraded land in Southeast Asia

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ABSTRACT

Gasification is recognized as a green technology as it can harness energy from biomass in the form of syngas without causing severe environmental impacts, yet producing valuable solid residues that can be utilized in other applications. In this study, the feasibility of co-gasification of woody biomass and food waste in different proportions was investigated using a fixed-bed downdraft gasifier. Subsequently, the capability of biochar derived from gasification of woody biomass in the rehabilitation of soil from tropical secondary forests on degraded land (adinandra belukar) was also explored through a water spinach cultivation study using soil-biochar mixtures of different ratios. Gasification of a 60:40 wood waste-food waste mixture (w/w) produced syngas with the highest lower heating value (LHV) 5.29 MJ/m^3—approximately 0.4–4.0% higher than gasification of 70:30 or 80:20 mixtures, or pure wood waste. Meanwhile, water spinach cultivated in a 2:1 soil-biochar mixture exhibited the best growth performance in terms of height (a 4-fold increment), weight (a 10-fold increment) and leaf surface area (a 5-fold increment) after 8 weeks of cultivation, owing to the high porosity, surface area, nutrient content and alkalinity of biochar. It is concluded that gasification may be an alternative technology to food waste disposal through co-gasification with woody biomass, and that gasification derived biochar is suitable for use as an amendment for the nutrient-poor, acidic soil of adinandra belukar.

1. Introduction

Food waste is a major problem that causes not only severe economic losses, but also significant environmental impacts. In Southeast Asia, it is estimated that 33% of food is wasted in the region (Teng and Trethewie, 2012). In Singapore, 796,000 tonnes of food waste were produced in 2013, which constituted almost 11% of the total waste generated, and with a poor recycling rate of 13% on all types of food waste produced (Singapore National Environment Agency, 2013). Typical food waste treatment methods are anaerobic digestion, composting, landfills and incineration (Thi et al., 2015). However, landfills can generate greenhouse gases and release polluted leachates that lead to ground water pollution (Laner et al., 2012; Goldsmith et al., 2012). Furthermore, since segregation of food waste from municipal solid waste is not well practiced especially in households of developing countries, mass incineration of such mixed waste in an oxygen rich environment produces highly toxic dioxins which can cause adverse health effects (Thi et al., 2015; Myrin et al., 2014; Bordonaba et al., 2011).

Gasification is a potential alternative technology to the above-mentioned approaches and it is more environmentally friendly. It is a thermal process which utilizes high temperature of above 800 °C and an oxygen-deficient environment to convert solid biomass into combustible synthetic gas or syngas (mainly H_2 and CO) (Ong et al., 2015; Rong et al., 2015). Under an oxygen deficient environment, dioxins production is also greatly minimized. The syngas produced

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has very strong industrial applications including being an energy source for electricity generation, as well as being a feedstock for formulation of high-value chemical products (Kirubakaran et al., 2009).

Since food waste consists mostly of rice, noodles, and vegetables which contain large amounts of carbohydrate, it has the potential to be gasified to produce syngas. Ahmed and Gupta (2010) studied the syngas characteristics from the pyrolysis and gasification of food waste (simulated as dog food) using a lab scale experimental facility with steam as the gasifying agent. The results showed that gasification offered better syngas yield, hydrogen yield and energy yield as compared to pyrolysis. This promising result motivated a study using real life complex food waste in an actual fixed bed downdraft gasifier. However, instead of direct gasification of pure food waste, it is important to first investigate the feasibility and compatibility of food waste in the gasifier. Furthermore, the high moisture content in food waste may have a negative impact on energy harvesting owing to the high latent heat of vaporization. This was done batchwise through co-gasification with woody biomass and slowly increasing the proportion of food waste, while observing how the quality of syngas changed in terms of its lower heating value (LHV) in addition to any possible operability issues encountered.

Besides offering the added benefit of producing syngas as discussed above, gasification may allow the nutrient content found in the feedstock to be captured in its solid by-product, biochar (Silber et al., 2010). Biochar has great applications in agriculture and environmental engineering to improve soil quality by enhancing the nutrient content (Lehmann and Joseph, 2012; Ventura et al., 2013), remediate pollution by adsorbing aromatic contaminants and heavy metals (Han et al., 2013; Regmi et al., 2012; Fuente-Cuesta et al., 2012), and avert global warming by sequestrating carbon (Spokas et al., 2012; Stewart et al., 2013).

For soil rehabilitation purposes, biochar can be applied to the nutrient-poor, acidic soil in adinandra belukar, a species-poor, anthropogenic, secondary forest found commonly in Singapore, southern Peninsular Malaysia, and the Riau Archipelago of Indonesia, within a 150-km radius of Singapore (Sim et al., 1992). The forest grows on degraded land caused by poor agricultural practices and its poor soil is characterized by a low pH range of 3.3–3.9 in the top 0–20 cm of the soil surface and low total nitrogen and phosphorus content. Consequently, fewer plant species are able to grow in adinandra belukar compared to primary tropical rainforests that grow on undegraded land. By applying biochar to soil, the positive features of biochar can help to raise the soil pH and nutrient level for a more optimum plant growth, enhance cation exchange capacity and decrease the tensile strength of compacted soil with its highly porous structure (Windeatt et al., 2014; Huff et al., 2014; Zheng et al., 2013; Sigua et al., 2015).

There are many studies in the literature that investigate the effects of biochar on both soil and various types of plant species. Méndez et al. (2012) studied the effects of biochar derived from pyrolysis of sewage sludge on plant metal solubility and mobility in Mediterranean agricultural soil. Graber et al. (2010) applied wood-derived biochar in the cultivation of pepper and tomato using soilless media, and studied its impact on plant productivity as well as the rhizosphere microbial populations. Meanwhile, Lee et al. (2010) characterized both pyrolysis and gasification derived biochars in terms of their cation exchange capacity in comparison to Alfisol soil. Although there are many exciting biochar research ongoing with excellent outcomes, there is limited research to understand the effect of gasification derived biochar on the rehabilitation of adinandra belukar soil in Southeast Asia. Therefore in this study, the rehabilitation capability was investigated through a cultivation study using water spinach (*Ipomoea aquatica*) as a plant model, with emphasis on the various growth indicators to quantify the performance and effects of biochar application.

In short, this study first aims to explore the capability of gasification as an environmental-friendly technology by tackling the problem of food waste through co-gasification with woody biomass in different proportions, using the syngas quality (lower heating value) as a performance indicator. Subsequently, the second objective is to investigate the rehabilitating capability of biochar on nutrient-poor, acidic soil in adinandra belukar, via the cultivation of water spinach (*I. aquatica*) at different ratios of soil-biochar mixtures.

2. Materials and methods

2.1. Pre-treatment and sorting of food waste

Food waste was collected from a canteen within the National University of Singapore Campus, College Avenue West, Singapore. The first few sample batches of food waste were sorted into categories including category A (rice, noodles, pasta), category B (meat, eggs), category C (vegetable matter), and category D (bones) in order to determine their overall average composition. Bones were eliminated as they were typically beyond the gasification feedstock upper size limit of 4 cm and tended to cause blockage in the feeding system and reactor. Each sample of the remaining categories was taken as 100 g and dried for 12 h using an Excalibur Parallex 9 Trays commercial food dehydrator before further analysis and gasification. Moisture content and dry weight of each category was calculated through the weight difference before and after the 12-h drying process. The subsequent experimental batches of food waste were no longer separated into different categories but the bones were removed, and it was assumed that the composition of the subsequent experimental food waste was similar to that of the sample food waste calculated above.

2.2. Feedstock characterization

The gasification feedstock in this study consisted of mesquite wood chips (KingsFord, USA) with a particle size range of 2.54–3.81 cm, and food waste with a wide size range (as small as 0.51 cm for rice, or as large as 2.54–3.81 cm for meat). Owing to its high moisture level (in the range from 54 to 82.7%), food waste was pre-dried (maximum allowable moisture level of 30% for steady-state gasifier operation) as outlined in section 2.1.

Thermal gravimetric analysis (TGA) was performed using a Shimadzu DTG-60AH thermal analyzer to do a proximate analysis of moisture, volatile, fixed carbon and ash contents of the feedstock. Briefly, the feedstock was heated from 25 to 800 °C at a rate of 20 °C/min under air and nitrogen atmospheres. Elemental analysis was carried out using a Vario MACRO Cube Elemental Analyzer. For the ultimate analysis which involved the detection of carbon, hydrogen, nitrogen and sulphur, a small amount of sample—approximately 3 g—was combusted at 1150 °C to produce CO_2, H_2O, NO_2, and SO_2. These gases were transported by a helium carrier gas and sent to the detector where the mass percentage of each element was calculated. The oxygen mass percentage was calculated by subtracting the mass percentages of C, H, N, S, and ash from 100%, assuming other elements being in very low concentrations.

The higher heating value (HHV) of feedstock was estimated using Equation (1) (Channiwala and Parikh, 2002).

$$\mathrm{HHV} = 0.3491{*}M_C + 1.1783{*}M_H + 0.1005{*}M_S - 0.1034{*}M_O - 0.0151{*}M_N - 0.0211{*}M_{ash} \tag{1}$$

where M_i: mass percentage of the element i (i.e. i = C, H, N, S, O and