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Life cycle assessment of fast pyrolysis of municipal solid waste in North Carolina of USA

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ABSTRACT

This study was to investigate whether a pyrolysis plant using municipal solid waste (MSW) in North Carolina would be environmentally friendly. Based on the analysis of primary landfills and wasteflow across North Carolina, five pyrolysis plants were assumed to be built to utilize MSW. Life cycle assessment results indicate that global warming potential (GWP), acidification potential (AP), human toxicity potential (HTP) and photochem ozone creation potential (POCP) are mainly from bio-oil production, which accounts for 32.8%, 59.4%, 98.2% and 99.8% of the total potentials generated by the whole process, respectively. Besides, the main source of ozone depletion potential (ODP) and terrestric ecotoxicity potential (TETP) is electricity for bio-oil production. Eutrophication potential (EP) emission is mainly from the exhaust of diesel vehicle operation. Hydrogen and char are produced in production and upgrading of bio-oil as co-products, which generate 5.5 MJ and 2.7 MJ energy credits per kg MSW, respectively. Sensitivity analysis indicates that the yield of bio-oil is the most sensitive parameter in determining GWP and the electricity consumption also plays a significant role on GWP. The impact potentials of MSW pyrolysis were compared with those of other three alternatives of anaerobic digestion, incineration and landfill for treating MSW. Results show fast pyrolysis for bio-oil causes the least impact, while the disposal of the MSW in landfills causes the worst impact on the environment. Based on above results, pyrolysis of MSW for transportation fuels is an environment-friendly way to utilize the MSW.

1. Introduction

Municipal Solid Wastes (MSW), commonly called “trash” or “garbage”, include wastes of durable goods, nondurable goods, containers and others. MSW generally refers to common household waste, as well as office and retail wastes, but excludes industrial, hazardous, and construction wastes. In 2010, Americans generated about 250 million tons of MSW, and recycled and composted over 85 million tons of the MSW, which was about 34.1% of the total MSW (US EPA, 2011).

Conventional handling of MSW using a large number of landfills causes serious environmental and public health concerns. One of the most important environmental issues is long-term leachate emission, which may pollute the surface water around the landfill. Organic matter, nitrogen and heavy metals were detected at higher levels than allowable limits. Another problem of landfills is pollutants emitted into air. The gas which is generated by the microbial degradation of organic matter in landfills under anaerobic conditions is mostly composed of 50–60% CH_4 and 40–45% CO_2 by volume. More than 200 non-methane volatile organic compounds make up less than 1% by volume (Rettenberger et al., 1996). Despite their low concentrations, these compounds which include aromatics, alkanes and halogenated hydrocarbons may exert adverse effects on the environment, both at global and local scales. In particular, landfill gas may contribute to ozone depletion due to chlorofluorocarbons (CFCs) and hydro-fluorocarbons (HCFCs) and increase risks of cancer for local residents.

Technologies to convert MSW into energy can be divided into thermo-chemical and biological conversion technologies (Biomass Energy Center. Co, 2008). Thermo-chemical conversion includes direct combustion to generate heat for power (Nan et al., 1994), gasification to break down MSW into gases (Biomass Energy Center. Co, 2008; Purohit, 2009), and pyrolysis to produce gas, char and liquid bio-oil (Nan et al., 1994). Biological conversion includes anaerobic digestion using bacteria to break down MSW into biogas, and fermentation to produce alcohol. Recently, thermo-chemical conversion of waste to energy becomes more and more important because of a number of advantages (Stehlík, 2009). It is much quicker than biological conversion that usually takes from several

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days to a month. Products derived from MSW thermo-chemical conversion, such as syngas and bio-oil, may be directly used as a fuel, added to petroleum refinery stocks, upgraded using catalysts to a premium grade fuel or used as a chemical feedstock. Specially, production of a liquid fuel product increases the ease of handling, storage and transport and hence the product does not have to be used at or near the recycling plant (Buah et al., 2007).

Fast pyrolysis is a thermal decomposition process in which biomass is decomposed by heat at a high heating rate in the absence of oxygen, leading to the production of char, bio-oil and gaseous products (Sheth and Babu, 2009). It can convert 75 wt% of the biomass into liquid bio-oil, which has various applications such as supplying energy for transportation, heating, and electricity generation (Czernik and Bridgwater, 2004; Xu et al., 2009). Fast pyrolysis of MSW can decrease not only the requirement of building more landfills because of increasing MSW production, but also the risk of air and water pollution from landfills. However, using of bioenergy does not automatically guarantee the total progress of sustainable production, conversion and distribution of the energy is environmentally friendly (Buchholz et al., 2009; Hall et al., 2009; Lardon et al., 2009; Martin et al., 2009; Ponton, 2009). The bio-oil production may have negative environmental impacts, such as increasing greenhouse gas (Bringezu et al., 2009). Therefore, life cycle assessment (LCA) is needed to assess the overall environmental impact of the process of bioenergy production (Humbert et al., 2009; Xu et al., 2009; Zhong et al., 2009). LCA has been introduced to many fields including waste management and treatment, and production of biofuel (Benetto et al., 2009; Kiatkittipong et al., 2009; Laner, 2009; Ometto and Roma, 2010; Yu and Tao, 2009; Steele et al., 2012). However, there is little report on LCA study of fast pyrolysis of MSW. In this study, LCA was conducted to assess the environmental impacts of production, upgrading and usage of bio-oil from MSW using the GaBi software.

2. Methodology

2.1. Description for the biofuel production pathway

The plant capacity for the fast pyrolysis and bio-oil upgrading facility is assumed to be 2700 metric tons per day of wet MSW and the bio-oil yield is assumed to be 50% of the wet MSW, Bio-oil production from MSW includes MSW transportation, MSW pelleting, MSW fast pyrolysis, bio-oil recovery, biochar collection, steam reforming, bio-oil upgrading, product distribution, and vehicle operation. In the step of MSW pelleting, MSW containing 40 wt% moisture is chopped and made into pellets at a size from 2.2 mm to 10 mm. Then the pellet was dried to less than 10% moisture. In the fast pyrolysis step, MSW produced approximate 20wt% of non-condensable hydrocarbon gases, 50wt% of bio-oil and 30 wt% of char in a fluidized bed reactor at 500 °C and ambient pressure. The bio-oil vapors are recovered using a condenser. 90% of the entrained char and ash particles are removed from the pyrolysis products through cyclones. The remainder of the char is treated as coal substitute locally consumed.

The bio-oil is separated into a water-insoluble phase and an aqueous phase using a liquid–liquid (L–L) extractor. The insoluble phase is upgraded to gasoline and diesel fuel through hydrotreating (Zhang et al., 2013). Through the reaction, it was expected that the quality of the hydrodeoxygenated bio-oil, in terms of the content of high-value hydrocarbons, i.e., cyclohexane and benzene, met the standard of a ready transportation fuel (Gutierrez et al., 2007). Hydrogen for upgrading was obtained from steam reforming of the aqueous phase of bio-oil. A portion of the hydrogen was used to hydrocrack the water-insoluble phase of the bio-oil, and the rest of the hydrogen was treated as a co-product and energy credit.

2.2. Goal and scope definition

The goal of this LCA study is to identify the environmental impact of the process of converting MSW to pyrolytic oil. Fig. 1 illustrates the system boundary for the LCA.

In the present study, required materials and energy inputs associated with the unit processes of the LCA were derived from the GaBi database (PE International), U.S. Life Cycle Inventory Database (National Renewable Energy Laboratory, 1999) and data in published papers (Buah et al., 2007). Energy for MSW pelleting and bio-oil production is from electricity grid generated by Duke Energy in North Carolina. The ASPEN Plus process model is adapted to simulate the upgrading of bio-oil from fast pyrolysis of MSW.

The detailed inputs and outputs in the unit process are shown in Fig. 1.

The following assumptions were used in the progress:

- All MSW was obtained from landfills. The transportation from the resident home to the landfill was not considered.
- Land use and construction of a plant were not considered in this study. Original MSW had 40% water content. MSW Pellet was dried to 10% before being pyrolyzed.
- Organics, plastics, papers and textiles were the components of MSW which could be pyrolyzed to produce bio-oil. They had been separated from MSW before being utilized and the separating process was not considered in this study.

2.3. Functional unit

In this study, functional unit is defined as 1 kg organic components in MSW utilized in the fast pyrolysis plant. All emissions, energy consumption, and materials are based on this functional unit.

2.4. Investigated regions

The chosen research areas are the administrative districts of North Carolina, USA. North Carolina disposed of a total of 9,467,045 tons of MSW in waste management facilities located within North Carolina in 2011 (United States Census, 2011). According to North Carolina landfill wasteflow (Mcmilen, 2007), there are 8 primary landfills, Wi-sampson county disposal Inc, Uwharrie environmental regional landfill, Upper Piedmont regional landfill, Foothills landfill, East Carolina landfill, Crswma-long term landfill, Chambers MSWlf and Bfi-Charlotte motor speedway landfill. Data of collected MSW in primary landfills in North Carolina is listed in Table 1. It indicates that Bri-Charlotte landfill is the biggest landfill in western NC and close to 3 other smaller landfills: Uwharrie, Foothills and Chambers (Fig. 2a and b) (North Carolina Solid Waste and Materials Management Annual, 2010). It is thus reasonable to build a pyrolysis plant near Bri-Charlotte landfill to utilize collected MSW in western North Carolina. For the same reason, pyrolysis plants can be built in another four locations near Wi-Sampson, Upper Piedmont, East Carolina and Crowma, respectively. Based on the above analysis and assumption, five pyrolysis plants can be built to utilize collected MSW in western NC, Central South NC, Central North NC, Northeast NC and Southeast NC respectively. As shown in Fig. 2b, the longest transportation is 160 mile and the average distance is considered as 100 mile in this study.

2.5. Impact assessment

In this study, the environmental design of CML (Centre of Environmental Science, at Leiden University, The Netherlands) methodology was chosen to be used. The impact categories were