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Environmental impact comparison of four options to treat the cellulosic fraction of municipal solid waste (CF-MSW) in green megacities

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ABSTRACT

Megacities are characterized by a high urban population density, and timely solid waste management is crucial for the wellbeing of its citizens. In this study, the cellulosic fraction of municipal solid waste is the target for management in Singapore (which has one of the highest population densities in the world) using four pertinent options – incineration, anaerobic digestion, gasification and composting. The energy sustainability and environmental impacts in the form of greenhouse gas emissions are considered for each scenario together with the status quo to achieve the most favorable recommendation, with a sensitivity analysis in the case that no bio-fertilizers are allowed for use locally. In terms of GWP and energy profile for grass waste, AD is the most environmentally friendly option (2 kilo tonnes of $CO_{2\text{-eq}}$ and 23.3 GWh respectively), while for leaf waste, gasification is the best, with AD a close second.

1. Introduction

Megacities are cities with more than 10 million people - with such a high urban population density, timely waste management is critical for the health and wellbeing of their residents. At the same time, an increasing awareness of environmental issues leads to a social requirement that the waste be managed in the most resource-frugal and environmentally friendly way possible. Singapore is a country of 5.4 million residents in an area of roughly 716 square kilometers (Statistics Singapore, 2014). Although it is not considered a megacity, the huge population density of 7540 people per square km means that it is suitable as a model for scaling up to cities which also face a large production of solid waste and limited land to dispose of it hygienically (Lee, 2008). Concomitantly, Singapore aims for her growth to be green and environmentally sustainable (National Climate Change Strategy, 2012). The confluence of all the above factors drives the impetus for assessing different alternatives for the treatment of municipal solid waste (MSW).

One significant portion of this waste is the cellulosic fraction of MSW (CF-MSW). In Singapore, trees and grasses are ubiquitous, in following with the governmental directive to achieve the status of being a Garden City. According to Ng (2008), the vegetation cover in Singapore grew from 35.7% to 46.5% between 1986 and 2007, and is set to increase even more with the new plan to transform her into a City in a Garden (Ng, 2008 and NParks Annual Report, 2013/2014). Indeed, Khoo et al. (2012) calculations based on data obtained from the National Environment Agency (NEA) from 1994 to 2010 showed that while the fraction of most wastes decreased due to recycling and other initiatives, the amount of horticultural waste (similarly for food, plastic and paper) bucks the trend. Although 48% of this waste is recycled (NEA, 2013), it is mainly the tree trunks and branches that undergo composting or wood recycling (private communications with NEA officials). These translate into having to dispose of an increasing amount of leaves each year.

Concurrently, Singapore faces a growing demand for energy must be met in a sustainable fashion by virtue of the need to reduce fossil energy consumption and greenhouse gas (GHG) emissions. Due to Singapore's geographical circumstances, Singapore is "alternative-energy disadvantaged" (Sustainable Singapore Blueprint, 2015). While renewable energy sources are available in other countries such as geothermal, hydro and wind energies are not able to be feasibly exploited, leaving scant options like solar power. Hence, Singapore relies heavily on natural gas as the main source of fuel (>95%) and the remaining are oil and coal (EMA, 2017). Tan et al. (2010) had calculated that 601 kg $CO_{2\text{-eq}}$/MWh impacts were generated for Singapore power grid (accounting for 2.5% transmission loss). Considering the need to meet growing

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demands for energy as well as commitment to reduce green house gases to combat climate change, therefore, increasing interest in anaerobic digestion (AD) as a solution on the grounds of a lower requirement for energy to operate such plants in the tropics. Anaerobic digestion had been identified as a mature technology in European countries and one of the most promising sources of renewable energy (Börjesson and Mattiasson, 2008). With AD, the CF-MSW can be digested to produce methane-rich biogas as well as nutrient-rich digestate that can be used as fertilizers. Besides recovering energy and saving on the production of mineral fertilizers, AD would also divert the non-incinerable portion of CF-MSW away from landfills, of which Singapore has only one. Semakau Island houses the last remaining landfill in Singapore, and current estimates project that it will be filled by 2035. In contrast, gasification is a much newer method than AD, and is especially good at converting low moisture biomass into syngas and biochar. As Nguyen and Hermansen (2015) put it, "gasification is regarded as an advanced and efficient method to extract energy from different biomass sources". Hence it would be a good alternative technology for a comparison against AD. Whilst there are many different gasification methods, e.g. the state-of-the-art Integrated Pyrolysis Regenerated Plant microturbine technology (Zampilli et al., 2017), the more commonly used downdraft gasifier will be the process examined in this study.

This study compares the performance of different waste disposal and energy recovery technologies (AD, Gasification, Incineration and Composting) for the treatment of CF-MSW, taking into account energy sustainability, and environmental impacts in terms of climate change potential, reported as kg $CO_{2\text{-eq}}$.

2. Materials & methods

2.1. Goal and scope

The intended application of this LCA is to quantify the potential environmental impacts arising from the current process of the management of cellulosic waste (leaf and grass) in Singapore, in accordance to ISO 14040:2006 framework. This study can benefit regulatory authorities in the Ministry of Environment and Water Resources (statutory board NEA) and the Ministry of National Development (statutory board NParks) or be incorporated into models of waste management.

The scope of the LCA covers the current and potential treatment for horticultural waste generated in public area (e.g. leafs from trees planted along road and grass on public land). In order to avoid subjectivity, CML life cycle impact assessment methodology (Guinée et al., 1993) have been adopted in this study. The category indicators used are global warming potential (kg $CO_{2\text{-eq}}$/yr) and energy use (MJ-$_{eq}$/yr) The impacts selected are based on local and current concerns relevant to Singapore and the work carried out in this article. In addition, a cut-off criteria of 3% have been used to facilitate the studies.

The system boundaries (Figs. 1 and 2) include output of bio-compost, which is assumed to be applied on land and replaces a certain amount of inorganic fertiliser. A sensitivity analysis was carried out for revised figures if this particular assumption could not be met. The functional unit is based on 1 tonne of leafs and 1 tonne of grass for easy comparison of technology.

2.2. Life cycle inventory

Data used in the LCI phase are obtain from scientific databases such as Ecoinvent (2017), experiment work and peer reviewed journal articles. The details on the experimental work carried out were further explain the next sub-section.

2.2.1. Analytical methods

Axonopus compressus was harvested from fields in Singapore by hand, vacuum dried overnight before being finely shredded in a blender, divided into 1.1 g aliquots and stored at −20 °C until use. The elemental composition of the grass was 42.57 wt% C, 6.35 wt% H, 2.62 wt% N and 0.51 wt% S, with a volatile solids (VS) content of 45.3%. The composition of the grass was cellulose content 42.5%, hemicellulose 27.1%, lignin 12.7%, ash 0.7% and neutral detergent soluble 16.7%. *Pterocarpus indicus* leaves were collected from 3 trees on the campus grounds of University Town, National University of Singapore, frozen at −20 °C, then finely shredded in a blender, divided into 1.1 g aliquots and stored at −20 °C until use. The elemental composition of the leaves were 46.22 wt% C,

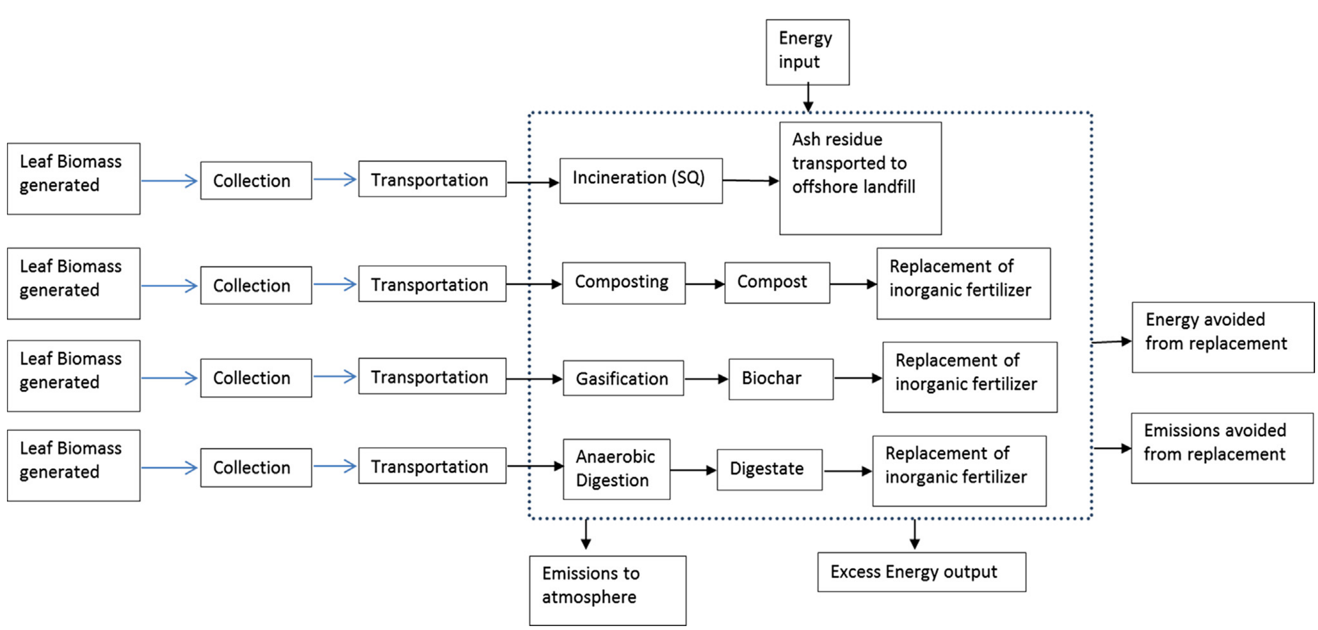

Fig. 1. System boundary for treatment of leaf material.