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Life cycle inventory and mass-balance of municipal food waste management systems: Decision support methods beyond the waste hierarchy

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ABSTRACT

When assessing the environmental and human health impact of a municipal food waste (FW) management system waste managers typically rely on the principles of the waste hierarchy; using metrics such as the mass or rate of waste that is 'prepared for recycling,' 'recovered for energy,' or 'sent to landfill.' These metrics measure the collection and sorting efficiency of a waste system but are incapable of determining the efficiency of a system to turn waste into a valuable resource. In this study a life cycle approach was employed using a system boundary that includes the entire waste service provision from collection to safe end-use or disposal. A life cycle inventory of seven waste management systems was calculated, including the first service wide inventory of FW management through kitchen in-sink disposal (food waste disposer). Results describe the mass, energy and water balance of each system along with key emissions profile. It was demonstrated that the energy balance can differ significantly from its' energy generation, exemplified by mechanical biological treatment, which was the best system for generating energy from waste but only 5th best for net-energy generation. Furthermore, the energy balance of kitchen in-sink disposal was shown to be reduced because 31% of volatile solids were lost in pre-treatment. The study also confirmed that higher FW landfill diversion rates were critical for reducing many harmful emissions to air and water. Although, mass-balance analysis showed that the alternative end-use of the FW material may still contain high impact pollutants.

1. Introduction

Municipal solid waste is known to make a significant contribution to many of the world's most critical environmental problems; including climate change, resource depletion and ecosystem damage. FW is typically the largest component of municipal solid waste in both developed and developing nations and, despite its biodegradable nature, is one of the biggest sources of pollution to water and the atmosphere stemming from solid waste management, particularly when landfilled (Laurent et al., 2014). Waste managers and policy makers the world over recognise the need to better manage FW. Many nations have thus implemented a number of legislative and policy tools in order to promote better management of FW from as early as 1997 (European Council, 2008; Kim et al., 2011; Kjaer, 2013; Zhang et al., 2014). Australia has recently implemented policy measures including landfill levies and incentivising source separation of FW (Edwards et al., 2015; Pickin, 2015; Randell et al., 2014). Yet, only 270,000 Mg of FW was sent for recycling in Australian for the fiscal year 2010/11, approximately 11% of municipal FW generated, with the remaining 2,720,000 Mg sent to landfill (Randell et al., 2014). Given this context and further increases to landfill levies, waste managers are seeking alternative methods of treating FW that both divert FW from landfill and achieve better environmental outcomes.

When assessing the environmental impact of a waste management system (WMS), in Australia, and in many other nations, the assessment is guided by the waste management and treatment hierarchy, which is written into legislation (Randell et al., 2014). The hierarchy detailed as highest to lowest in priority is as follows (1) avoidance and the reduction of waste generation, (2) the re-use of waste i.e. cleaning and re-filling glass beverage containers, (3) the recycling of waste into alternative products, (4) the recovery of energy from waste, (5) treatment and disposal. Governments at all levels are henceforth interested in reducing waste as per

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priorities 1 and 2, and where waste is inevitably generated, governments are interested in a management systems' ability to maximise the quantity of waste recycled or used to recover energy. However, there is a gap in the knowledge concerning the quantification of waste a system can recycle, recover or dispose of; with data rarely being reported or published. Moreover, when it is reported, measures typically refer to the mass or rate at which waste is 'recovered for recycling' or 'recovered for energy generation,' referring to the waste that has been made available as an input into a physical or chemical process that generates a valuable product, substance or material (Carre et al., 2014; Randell et al., 2014). This definition is distinct from the mass of a useable product, material or substance derived from a waste. Measuring the quantity of waste 'recovered for recycling' is not able to show the efficiency of a recycling or energy recovery system (Bartl, 2014; Gharfalkar et al., 2015).

Bartl (2014) suggests three criteria in order to measure a systems efficiency pertaining to (1) how much material is lost, (2) what is the quality of the product, material or substance created, and (3) what is the energy and water demand. A mass-balance is a useful method of determining these criteria, as it is capable of mapping where materials are lost from a system, the quantity of elements, which are key quality indicators like N:P:K or methane and when applied to the biosphere, and when an energy balance is also, included energy consumption and generation can be shown. Yet, there is an absence of knowledge regarding the mass-balance of a whole WMS, from collection to treatment, and to ultimate end-use. Previous mass balance studies have been completed within the context of a waste treatment facility or single treatment process (Schievano et al., 2011; Spokas et al., 2006; Yoshida et al., 2015; Zhang and Matsuto, 2011, 2010). However, few studies focus on the path taken after the treatment facility, for example; the mass of the nutrients within waste derived compost that is available to plant life when applied to land, the mass of biogenic carbon stored in the humus, or the mass of methane in landfill gas or biogas that is combusted for energy generation.

This study circumvented this issue by taking a life cycle approach to mass-balance modelling; extending the boundary to include the collection, pre-treatment and end-use of the waste. Completing the mass balance of systems in this manner enables a waste system model to incorporate the principles of the circular economy, more explicitly allowing for; (1) a complete assessment of a wastes pathway to a valuable product or to disposal, (2) the identification of inefficiencies within a current recycling or recovery system, and (3) the comparison of systems in accordance to the amount of waste that each system recycled or recovered for energy.

The study also provides the life cycle inventory (LCI) for six commonly applied WMS and one atypical approach involving kitchen sink disposal. The systems include; FW being sent to landfill (BAU), composted with garden organics in a centralised facility (COMP), composted at home (HCOMP), FW being mechanically separated, digested and then aerobically treated (MBT), and source separated FW that is either separately digested (SAD), or co-digested along with sewage sludge (AcoD). The final WMS is the first published inventory for a waste management system based upon the kitchen in-sink maceration of FW that is transported by the sewer system to the local wastewater treatment plant (WWTP) where it forms a component of the sewage sludge and is anaerobically digested (INSINK). The INSINK system, is an infrequently and informally used system, however has been included in the study as it represents an innovative method for collection and transportation of FW to a WWTP where anaerobic co-digestion with sewage sludge can occur. Anaerobic co-digestion, according to previous work has been shown to significantly boost the energy recovery efficiency of waste management systems and therefore was a prime focus of the study (Righi et al., 2013; Zupančič et al., 2008).

The LCI was used to determine the net-energy and water demand of all WMS as well as the emissions of key pollutants to the environment, so as to be used in a subsequent life cycle assessment. The study focused on two local government areas as case studies that provide the reference flow of waste as well as real life variables. This is the first life cycle inventory of many of the WMS modelled in the context of Australia. By using two case studies the research demonstrated the nuances across waste catchments, moreover, investigated whether systems showed consistent performance, despite the different variables imposed by each case study.

2. Materials and methods

WMS are modelled in the context of two unique Australian case study local government areas with the primary function of each system to safely collect and treat all municipal solid waste including food waste (FW) and inert residual waste, which is discarded to the 80–120 L kerbside collected mobile garbage bin (MGB); garden waste (GW), that is discarded to the 240 L kerbside collected mobile organics bin (MOB) and sewage sludge (SS) which is a by-product of municipal wastewater treatment. Recyclable items (e.g. glass, plastics, and metals) discarded by inhabitants into the kerbside recyclable bin were excluded from this study as they were managed in the same manner throughout all WMS. However, recyclables misplaced into the MGB were implicitly included in the study as they are reported as contributions to the categories within MGB waste i.e. paper/cardboard.

The functional unit was defined as *"the management and treatment of the annual quantity of MGB and MOB waste collected by the local government, and the annual quantity of sewage sludge treated by the local WWTP."*

2.1. Case study area and flows

The two case studies modelled are Melton City Council (MCC), located in the outer suburbs of Melbourne, Australia and Sutherland Shire Council (SSC) an inner suburban suburb of Sydney. The two case studies and their associated waste flows are detailed in (Edwards et al., 2017).

2.2. Description of waste management systems and system boundary

The LCA system boundary incorporated the entire waste management service provision and was divided into four distinct unit process stages; collection, pre-treatment, treatment, and end-use/disposal. The zero burden approach was taken i.e. the notion that no environmental impact is designated to the waste from prior production, transportation and use stages (Turner et al., 2016). *Unit process I – Collection* – was the kerbside collection of mobile wheelie bins. *Unit process II - Pre-treatment* – was a physical or chemical process that sorted wastes into homogenous waste streams in order to ensure the downstream treatment operates effectively, in doing so waste may also be partly degraded or its characteristics altered. *Unit process III – Treatment* – referred to a waste stream entering; landfill, composting, or anaerobic digestion technology. The final unit process, *Unit process IV – end-use/disposal* – represented the destination process of the waste stream after treatment, and included waste remaining in landfill or being applied to land as either biosolids or compost.

Each WMS was named after the manner in which it treats FW excluding business-as-usual which represents the current WMS in each case study. The seven WMS modelled are;