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Impact of organic waste composition on life cycle energy production, global warming and Water use for treatment by anaerobic digestion followed by composting

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ABSTRACT

In response to significant organic waste generation, environmental policies are increasingly mandating diversion of organic waste from landfills and promoting alternative management practices to produce energy and reduce greenhouse gas emissions (GHG). Anaerobic digestion and composting are organic waste treatment alternatives, however, both practices require careful management to prevent similar environmental impacts as landfills. A model was developed to assess the impact of anaerobic digestion followed by composting of food waste and green waste mixtures on net energy production, global warming potential and scarce water use. The model included the ability to vary the initial organic waste composition, decomposition kinetics and treatment time. Energy needs for composting aeration and water pumping, and water use decreased as anaerobic digestion time increased. Composting water use savings for an organic waste anaerobically digested for 90 days prior to composting compared to zero days prior to composting ranged between 25%–53% for different organic waste compositions (from 1:0 to 0:1 green waste to food waste ratios), and energy use savings for composting aeration and water pumping ranged between 15%–17% and 24%–54%, respectively, for the same conditions. For an anaerobic digestion pretreatment time of 30 days prior to composting, the analysis predicted scarce water use to be 0.31–1.09 m^3 sw_e/Mg waste, primary energy use to be −168.5–298.3 MJ/Mg waste, and global warming potential to be 8.1–26.4 kg CO_2e/Mg waste. The results will help inform the design and maintenance of waste treatment in resource-limited environments.

1. Introduction

Over 46% of the global solid waste is organic waste (Hoornweg and Bhada-Tata, 2012). The United States alone produces 71 million tons of organic waste, including food waste and yard trimmings, annually, which makes up 28% of the country's total municipal solid waste stream (EPA, 2014). Environmental policies in the U.S., and particularly the state of California, are increasingly mandating diversion of organic waste from landfills and promoting alternative management practices to produce energy, prevent and reduce greenhouse gas (GHG) emissions, and preserve landfill space (California, 2014).

Organic waste can be managed and valorized through anaerobic digestion (AD), composting and mulching to produce useable forms of renewable energy and soil amendments, thus reducing waste disposal (Wei et al., 2017; Hebda et al., 2016). AD is a process where the decomposition of organic matter occurs in the absence of oxygen while composting is a process that is managed to facilitate aerobic decomposition of organic matter. Although AD and composting have been cited as acceptable alternatives for treating organic waste, both practices require careful process management to ensure these treatments do not produce similar environmental impacts as landfills, including GHG emissions associated with poor process control. These management practices often rely on understanding the biological composition of the organic waste and its decomposition during composting and AD (Wei et al., 2017).

Compared to composting, AD is better suited for readily degradable

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organic residues, including food processing wastes, as it can produce methane that can be captured and used for energy production. Compost systems are more efficient than anaerobic digestion at degrading woodier biomass, such as yard waste, and can produce high quality soil amendments beneficial to agriculture (Tuomela et al., 2000; Martínez-Blanco et al., 2013a; Shiralipour et al., 1992; Aggelides and Londra, 2000). However, composting requires aeration and water replenishment to maintain optimal conditions for microbial activity. After treatment with AD or composting, the organic product can be land applied for agricultural or landscaping purposes as a fertilizer or soil amendment (Aggelides and Londra, 2000; Cheng et al., 2007; Heimersson et al., 2017). However, direct land-application of digestate from AD may produce uncontrolled GHG emissions because degradable substrate, phytotoxins, and methanogenic microbiota remain in the waste (Kirchmann and Bernal, 1997).

From a process sustainability and soil amendment quality perspective, pretreating organic waste using AD prior to composting to convert a portion of the organic carbon to energy has several advantages. Pretreatment has the potential to reduce water use, energy for aeration, and emitted GHGs during composting and improve the final compost quality compared to direct composting of the raw feedstock (Abdullahi et al., 2008; Smidt et al., 2011). This can be particularly pertinent in locations where resources, including water, money, and energy, are scarce. Likewise, post treatment of digestate using composting may improve the quality and suitability of the product for soil amendment and reduce GHG emissions upon application. Waste management practitioners, municipalities, and farmers need decision making tools to help them determine effective strategies for treating organic waste that have minimal impact on the environment based on feedstock composition and location.

Life cycle assessment (LCA) is a method to evaluate the potential environmental impacts a product, process, or service has throughout its life cycle (ISO, 2006). It can help identify environmental hotspots in a system, provide valuable information about the direct and indirect environmental impacts of a system, and be used as a design and decision-making tool to maximize environmental benefits. There have been many LCA models developed for analysis of anaerobic digestion and composting as summarized in Table A1. While each study evaluated different organic waste types, with the exception of one study, the input organic waste composition remained constant (Saer et al., 2013). Out of the 30 studies summarized in Table A1, six analyzed the impact of combining AD and composting to treat organic waste. Results for one study showed reduced impacts for global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), and ozone depletion potential (ODP) when AD and composting were combined compared to separate operation (Righi et al., 2013). A second study found there was no clear evidence that AD combined with composting was better than large scale composting tunnels alone with regards to GWP and other impact categories unless energy and material recovery were included in the evaluation (Montejo et al., 2013). Furthermore, only one study evaluated AD under high-solids conditions (Angelo et al., 2017) and it relied on secondary data.

The most common metrics used to evaluate the treatment processes in these prior studies were total energy use, GWP, AP, and EP. One key metric missing from many of these LCAs was the impact of water use in waste treatment processes. Four studies recorded water used during the life cycle inventory (LCI) stage, but they did not include an impact category or characterization factor for water use (Righi et al., 2013; Cadena et al., 2009a; Bernstad and la Cour Jansen, 2011; Lundie and Peters, 2005). Water use is especially important for organic waste treatment because geographic regions with high agricultural yields and practices produce large amounts of agricultural residue that require waste management strategies to dispose at that scale, (Ward et al., 2008) and these regions also are commonly found in areas with high water stress (Schlosser et al., 2014). Analyzing the impact of water use is increasingly important for analyzing alternative organic waste treatment systems that are environmentally preferable to landfilling. Landfills typically do not require water input for waste disposal, but composting and AD often require water addition for important biological functions involved in organic matter decomposition.

The main objective for this study was to develop a LCA model that incorporated mass and energy balances for AD and composting and varying feedstock composition to evaluate an energy production and organic waste treatment system. The analysis was conducted as an attributional study to determine the impacts of these combined organic waste treatment technologies and their relevance to municipal energy production, solid waste disposal and reduction of GHG emissions. An attributional approach was selected because the study aims to analyze the baseline performance of this system. This baseline analysis can be used to compare current treatment technologies, which can help shape policy decisions. Due to its relevance for policy mandates related to organic waste diversion from landfills, as well as new technology development and implementation for waste treatment, this study's work has the potential to effect policy, municipal solid waste management, municipal landfill and AD operations and product development.

2. Methods

LCA assesses the environmental impacts of a product, process, or service throughout its life cycle. It tracks the inputs and outputs of energy, raw material consumption, emissions, and other wastes at each life-cycle stage (ISO, 2006). The main phases of an LCA, defined by the International Organization for Standards (ISO) 14,000 series, are goal and scope; inventory analysis; impact assessment; and interpretation.

2.1. Goal and scope

LCA methods were used to assess the environmental impact of energy production and treatment of food waste and green waste mixtures (organic waste) using AD and composting. The model was demonstrated for the Central Valley region in Northern California, although the data may potentially represent waste streams elsewhere since a range of waste mixtures was examined. The basis for comparison of AD and composting management practices and feedstock compositions included three impact categories: GWP based on IPCC AR5 characterization factors over 100 years, primary energy use, and water use impact (stressed water) determined using an impact assessment method described elsewhere (Pace, 2017; IPCC, Climate Change, 2014). All impact categories were based on a functional unit defined as the treatment of 1 metric ton (1 Mg) of organic waste.

The system flow diagram is shown in Fig. 1. The system boundary included transportation of organic waste to the facility, material separation, grinding, AD followed by composting of digestate (compost), biogas clean-up (moisture and H_2S removal), production of electricity, flaring excess biogas, and overall operation and maintenance for system processes, including transportation on site (see Table 1). The baseline system analysis did not include system expansion to credit excess electricity delivered to the grid or compost as soil amendment. During scenario analyses, compost as soil amendment and electricity converted from the biogas generated from the anaerobic digester were assessed as co-products of the treated organic waste using system expansion methods. Consumer use of co-products was excluded from the life cycle inventory (LCI) due to limitations of data collection and uncertainty. Additional life cycle modules excluded from the organic waste treatment systems' LCI were burdens contributed by capital equipment and/or human operators, and disposal of co-products. Organic waste production was not attributable to the valorizing system and was not included in the system boundary. LCA modeling was conducted using Microsoft Excel.