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Evaluation of landfill gas emissions from municipal solid waste landfills for the life-cycle analysis of waste-to-energy pathways

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ABSTRACT

Various waste-to-energy (WTE) conversion technologies can generate energy products from municipal solid waste (MSW). Accurately evaluating landfill gas (LFG, mainly methane) emissions from base case landfills is critical to conducting a WTE life-cycle analysis (LCA) of their greenhouse gas (GHG) emissions. To reduce uncertainties in estimating LFG, this study investigated key parameters for its generation, based on updated experimental results. These results showed that the updated parameters changed the calculated GHG emissions from landfills significantly depending on waste stream; they resulted in a 65% reduction for wood (from 2412 to 848 t CO_2e/dry t) to a 4% increase for food waste (from 2603 to 2708 t CO_2e/dry t). Landfill GHG emissions also vary significantly based on LFG management practices and climate. In LCAs of WTE conversion, generating electricity from LFG helps reduce GHG emissions indirectly by displacing regional electricity. When both active LFG collection and power generation are considered, GHG emissions are 44% less for food waste (from 2708 to 1524 t CO_2e/dry t), relative to conventional MSW landfilling. The method developed and data collected in this study can help improve the assessment of GHG impacts from landfills, which supports transparent decision-making regarding the sustainable treatment, management, and utilization of MSW.

1. Introduction

An estimated 234 million metric tons (Mt) of municipal solid waste (MSW) generated in the United States in 2014, 52.6% of which (123 Mt) was discarded in landfills (USEPA, 2016a). Because of its considerable energy potential and high organic content, MSW has received increasing interest as a feedstock for fuel and energy production (i.e., waste-to-energy [WTE]). As the U.S. Department of Energy (DOE) recently stated, using MSW for fuel and energy production has several advantages (USDOE, 2017). For example, waste feedstocks are available at low prices, or even at negative prices considering tipping fees. Waste feedstocks also can be collected using the current infrastructure for waste collection and separation, which further lowers the cost of waste-derived energy products. In addition to these economic advantages, diverting waste feedstocks from landfills for energy production avoids the emissions that otherwise would occur with landfilling. The U.S. Environmental Protection Agency (USEPA) reported that greenhouse gas (GHG) emissions from waste landfills amounted to 115.7 Mt of carbon dioxide equivalent (CO_2e) in 2015 (USEPA, 2017). Waste-derived fuels can displace conventional fossil fuels, and avoiding the energy use and emissions associated with the production of the fossil fuels can provide additional benefits.

To take advantage of these benefits, several biochemical (e.g., anaerobic digestion and fermentation) and thermochemical (e.g., hydrothermal liquefaction, pyrolysis, and gasification) processes are currently being researched to convert MSW to fuels. For example, anaerobic digestion has been used to produce biogas and renewable natural gas from food waste (Lee et al., 2016). Fermentation processes that generate bioethanol from MSW also have been investigated (Lee et al., 2016). Both pyrolysis and gasification processes convert MSW to fuel using thermochemical processes. Pyrolysis processes convert waste into bio-char, bio-oil, and gases (Chen et al., 2015), and this bio-oil can be further hydroprocessed to produce gasoline and diesel blendstocks (Wang et al., 2015). The gasification process generates syngas, which can be converted into various fuels (e.g., Fischer-Tropsch diesel and jet) (Lee et al., 2014). Hydrothermal liquefaction is a way of generating liquid fuels from organic materials such as MSW (Dimitriadis and Bezergianni, 2017).

Life-cycle analyses (LCAs) have been conducted to evaluate the energy and environmental impacts of these MSW-based fuel production pathways. A major LCA issue for these pathways is treating

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carbon emissions. One approach is to use the carbon neutrality assumption (zero carbon emissions from the combustion of energy products) for carbon in organic waste as the Intergovernmental Panel on Climate Change (IPCC) and USEPA do (IPCC, 2008; USEPA, 2010). Using the assumption of carbon neutrality, Kalogo et al. (2007) examined a MSW-to-ethanol facility, Pressley et al. (2014) assessed the conversion of MSW to liquid fuel through gasification and Fishcer-Tropsch, and Vergara et al. (2011) evaluated five waste treatment strategies in California.

The other method is a marginal approach, which evaluates the impact of waste diversion on the production of MSW-based fuels. This approach was used for several waste management LCAs. Chester and Martin (2009) examined cellulosic ethanol generated from MSW. The California Air Resources Board (2016) estimated GHG emission reductions by diverting landfilled waste to compost facilities. Lee et al. (2016) studied compressed natural gas and ethanol production from MSW. For the marginal analysis approach, two scenarios are needed: a scenario where fuel is produced from waste (the alternative scenario), and a scenario that assumes business as usual (the counterfactual scenario). The marginal approach accounts only for the differences between the two scenarios to assess energy and the environmental effects of the alternative scenario. Usually, these LCAs assume that MSW used for energy and fuel production in the alternative scenario would otherwise be landfilled (i.e., the counterfactual scenario).

Emissions associated with landfilling waste need to be estimated for the counterfactual scenario. One way to estimate emissions from landfilled waste is to directly measure the emissions from landfills. However, in practice, emissions from a mixture of waste streams are usually measured together at a certain point in time, while an LCA study requires lifetime emissions from specific waste streams (e.g., food waste, yard trimmings). Another way is to use engineering models to estimate the generation, collection, and oxidation of landfill gas (LFG). For example, first-order decay models are commonly used to estimate LFG generation as suggested by the IPCC (IPCC, 2008) and the USEPA's Landfill Gas Emissions Model (LandGEM) (USEPA, 2005).

Given the estimated LFG generation, LFG collection efficiency and a methane (CH_4) oxidation factor are used to estimate LFG collection and oxidation. Estimated emissions that use these modeling approaches are highly sensitive to a few key parameters: LFG generation depends largely on the types of waste components and climate conditions, and CH_4 collection depends on decay speed over time, which varies widely among waste components, LFG collection strategies, landfill cover types, climate conditions, and oxidation factors. Several previous studies used the IPCC and USEPA methods. For example, Bogner and Matthews (2003) evaluated global CH_4 emissions from landfills, and Kennedy et al. (2010) estimated GHG emissions from global cities.

To conduct LCA of the WTE pathways, it may be necessary to estimate emissions of counterfactual scenarios for specific waste streams with specific parameters. This study evaluated key parameters to estimate the emissions specific to major landfilled organic waste types (i.e., paper, wood, food, and yard trimmings) using available experimental data to improve the accuracy of our LFG emission simulations under the counterfactual scenario. Because the emissions in the counterfactual scenario can be avoided if WTE technologies displace current landfills, this study will enhance the reliability of LCAs for various WTE pathways.

2. System boundary

Once organic waste is landfilled, it starts decomposing under anaerobic conditions and generates LFG, a mixture of CH_4 and carbon dioxide (CO_2). Simulations of LFG generation are based on the assumption that the decomposition of degradable carbon remaining in the landfill follows first-order decay characteristics, and the simulation parameters are adjusted using measured data. Once generated, LFG is collected and its CH_4 is combusted to reduce global warming impacts. During CH_4 combustion, landfill operators may generate electricity to improve their revenue instead of flaring LFG. In this case, it is assumed that regional electricity is displaced, which leads to reductions in GHG emissions because it avoids the emissions associated with regional electricity generation. Not all LFG generated can be collected, and some of it passes through landfill covers and is emitted to the atmosphere. While LFG goes through landfill covers, a portion of non-collected CH_4 oxidizes into CO_2. In summary, while CO_2 generated is emitted without being converted into other molecules—regardless of LFG collection conditions—a portion of CH_4 generated from landfilled waste is combusted or oxidized into CO_2.

Because CH_4 has a higher global warming potential (GWP) than CO_2, the fate of CH_4 is important in estimating the GHG emissions from landfilled waste. Fig. 1 represents the fate of CH_4 generated from waste decomposition, and LFG emissions are expressed as the sum of four emission components: (1) CO_2 emissions from collected CH_4 combustion, (2) non-collected CH_4 emissions, (3) CO_2 emissions from oxidized CH_4 in the landfill cover, and (4) CO_2 emissions from waste decomposition. Note that total carbon emissions in these emission components are determined only by the LFG generation process (i.e., decomposition of degradable organic carbon). The share of carbon emissions among these four emission components depends on the CH_4 concentration in LFG, LFG collection efficiency, and CH_4 oxidation factor. In order to

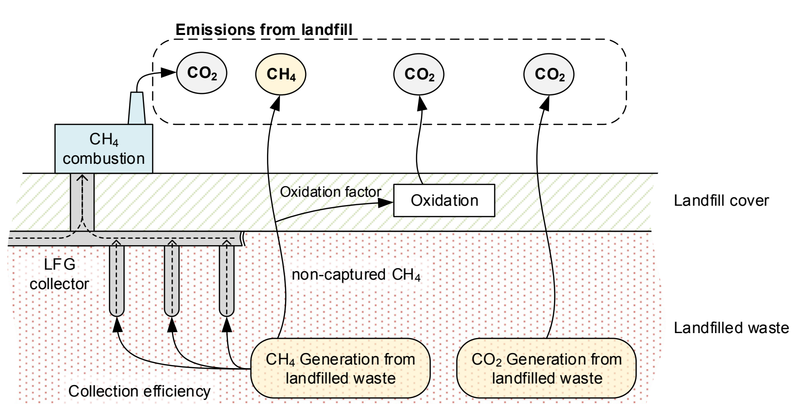

Fig. 1. Fate of LFG emissions generated from landfilled organic waste.