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Determining economically optimal household organic material management pathways

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ABSTRACT

This article presents a model to determine profit-maximizing processing pathways for urban household organic material. It was applied to a case study system in the city of Rochester, NY to compare the profitability of local material management pathways. Four industrially relevant and locally available pathways were examined: anaerobic digestion (AD), simultaneous saccharification and fermentation (SSF), windrow composting, and landfill with gas capture. This research hypothesized that the current status quo of landfill with gas capture is profit-maximizing, and formulated objective functions based on alternate practices of AD, SSF, and windrow composting to test the status quo. Material chemical parameters such as biomethane potential and carbon to nitrogen ratio were experimentally determined and used as inputs. The baseline model showed the status quo of landfill with gas capture is 52–92% less profitable than optimal pathways depending on ranges of input parameters. Optimal pathways were AD for single-stream and food, composting for compostable paper, and SSF for yard trimmings. Composting was the most sensitive pathway to market and chemical variables. AD being the optimal pathway is robust for food waste compared to landfill with gas capture; to reach parity with AD, landfill tipping fees must double or AD trucking costs triple.

1. Introduction

Three organic materials – food, yard trimmings, and compostable paper – make up about 30% of all municipal solid waste (MSW) in New York State (NYSDEC, 2008). About half of that is from household sources, which is equivalent to 15% of total MSW generated. Household organic material (HHOM) is defined as MSW generated at the residential level that is comprised of yard trimmings, food, and compostable paper (Environmental Protection Agency, 2013c). Yard trimmings include grass, leaves, and tree or brush trimmings. Compostable paper is food-soiled paper that is not compatible with traditional paper recycling processes.

Nationwide, over 70% of these materials are landfilled (Environmental Protection Agency, 2013a). Urban households are a specific area of concern as they are densely populated, produce more MSW than the commercial sector (NYSDEC, 2008), and often require costly trucking to distant landfills. In addition, urban MSW generation is estimated to increase significantly as urbanization progresses. Indeed, residential generation of all three resources has been increasing in the US from 2000 to 2012 (Environmental Protection Agency, 2013a).

Methane produced from landfilling organic material resources accounts for 9% of the global warming potential associated with U.S. emissions (Environmental Protection Agency, 2013b). Methane is a potent greenhouse gas (GHG), with over twenty times the global warming potential of carbon dioxide. Nearly 20% of US methane emissions come from the decomposition of organic materials in landfills (Environmental Protection Agency, 2013b).

Moving forward, sustainable household organic material management in the US will require the utilization of material processing pathways that are less GHG intensive than landfilling, while simultaneously improving on the profitability of status quo pathways. Municipalities have the option of investing in profitable local HHOM management pathways that offset the use of virgin materials, recycle nutrients for agriculture, and reduce greenhouse gas emissions (e.g. Sanscartier et al., 2012).

In this paper, four processing pathways that utilize HHOM feedstocks are analyzed for the case study city of Rochester, NY, primarily because they are feasible and regionally active. They are landfills with gas capture, anaerobic digestion (AD), simultaneous saccharification and fermentation (SSF), and windrow composting. Landfills with gas capture collect landfill gas formed from the

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anaerobic decomposition of organic material and combust it to produce electricity. AD is the conversion of organic material into biogas and compostable material (i.e. digestate) using anaerobic bacteria. It can be profitable for farm-based anaerobic digesters to accept food waste materials to achieve higher biogas yields through co-digestion (Rankin, 2013). Composting is the process of aerobic decomposition of organic materials into rich soil amendment. Windrow composting was analyzed in this research. This common commercial process produces compost by piling organic material in long rows, then periodically turning them and adding water to improve production efficiency. SSF is a proven technology for converting HHOM into ethanol, compost, and animal feed products.

From an environmental perspective, life cycle GHG emissions of HHOM management are reduced by utilizing AD (Sanscartier et al., 2012), SSF (Kalogo et al., 2007; Chester and Martin, 2009) and composting (Environmental Protection Agency, 2013c) in place of landfills (Cherubini et al., 2009). These GHG reductions are achieved by directly offsetting conventionally produced goods with functionally equivalent (or superior) goods from HHOM management pathways. For example, ethanol produced from SSF can be used as a transportation fuel (Kalogo et al., 2007). The three alternative pathways have unique social advantages in that they manufacture local products that help achieve food security (e.g. compost for community supported agriculture, food for animal and/or human consumption) and energy security (e.g. local biogas to offset imported fossil fuels).

Despite the potential for superior economic, environmental, and social performance of these non-landfill pathways, the US organic material landfill diversion rate is falling – down a combined 5% in the last five years on record (Environmental Protection Agency, 2013a). Excess food, yard trimmings, and compostable paper rank 1st, 5th, and 9th respectively in total household MSW generation out of the 19 tracked materials (NYSDEC, 2008). However, food and compostable paper are ranked last in landfill diversion (18th and 19th). One percent of food, less than one percent of compostable paper, and 67% of yard trimmings are managed in non-landfill pathways.

In contrast with most of the United States, Europe has pushed to reap the benefits of sustainable HHOM management. European HHOM has been increasingly diverted from landfills to organic waste-to-energy and composting pathways. By 2009, the EU reduced the mass of MSW going to landfill by 32% and increased the mass of organic material composted by 239% relative to 1995 levels (European Commission, 2011). This has been driven by policy that has increased MSW landfill diversion. For example, the European Union Landfill Directive of 1999 mandated a reduction in landfilling of biodegradable material to 35% of 1995 levels. Simultaneously, economic incentives have increased the profitability of non-landfill pathways (e.g. feed-in tariffs for renewable electricity generation). The resulting private and public sector investments in European HHOM processing pathways have enabled economies of scale and enhanced supply chain efficiency.

In the United States context, these strong policy levers are absent. Without clear price signals demanded by policy, local municipal and private decision-makers face very high uncertainty when investing in HHOM management pathways. Local planners usually have limited resources to evaluate the alternatives, and pilot programs can be expensive, time consuming, and inconclusive. In the absence of market intervention, classical economic theory predicts that commercial HHOM pathways that clearly maximize profits will be utilized over those that do not. As such, prior to our analysis it was assumed that landfilling has superior profitability as an HHOM management pathway, which would explain its usage at the expense of social and environmental performance. Fiscally responsible public and private decision-makers would benefit if they could verify that local resources such as HHOM are being optimally utilized.

Prior work in material management system design has advanced decision-making models to determine optimal management pathways. One team (Anex et al., 1996) developed a steady-state spreadsheet-based model that examines material management costs in a modular framework. This model has superior applicability for local public decision-makers, as it is meant to be tailored to reflect local conditions and calibrated to local data, however was limited to an examination of cost only. Similarly, more recent and advanced models (Den Boer et al., 2007; Münster et al., 2015) include holistic environmental and social indicators weighted against system costs. Analysis of the overall profitability of the material management pathway is a strong indicator of economic system sustainability for both the private and public sectors. An economic optimization model put forth by Diamadopoulos et al. (1995) thoroughly examined the potential profitability (i.e. net of revenues and costs) from increased recycling of landfilled materials, although the authors did not allow for comparison of different recycling technologies (i.e. management pathways) in a competitive marketplace. Thus, local application of the model may not produce optimal economic benefit due to a suboptimal choice of material management pathway.

Other work has used a technology-focused approach to modeling optimal material management systems. The Environmental Protection Agency (2010) released the Co-digestion Economic Analysis Tool (CoEAT) specifically for organic material. CoEAT is an engineering economic model which aims at defining; "initial economic feasibility of food waste co-digestion at wastewater treatment plants for the purpose of biogas production" (Environmental Protection Agency, 2010). However, the scope of CoEAT does not address the viability of the AD pathway in a competitive environment with other profitable management pathways. The EPA developed a broader model called the Municipal Solid Waste Decision Support Tool (MSW-DST). It is designed to analyze the life cycle costs and environmental impacts for alternative MSW strategies. However, it currently does not include increasingly common AD, SSF and other HHOM processing pathways – the comparison of which is necessary for material management decisions where these competing technologies are available.

To address these gaps, this research examined the relative profitability of HHOM management pathways with an engineering economic model as feed-in to an optimization model. The main goals of the model were to: (1) examine the relative profitability ($/kg processed) of each available HHOM management pathway; and (2) identify key parameters in the organic material management system that strongly affect pathway profitability. Model inputs included pathway revenues, pathway costs and feedstock chemical parameters from published data and experimental testing.

2. Methods

2.1. Optimization model

2.1.1. Model formulation overview

The model computed the profit-maximizing pathways for HHOM as the difference between total costs (i.e. operations; administration; capital financing) and total revenues (i.e. product and service sales; tipping fees). Organic material management pathways generated product revenue through biochemical processes with varying product yields, depending on the chemical parameters of the feedstocks. HHOM consisted of three distinct feedstocks (i.e. food, compostable paper, and yard trimmings) with unique chemical parameters (e.g. moisture, sugar content, biomethane potential).