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Environmental performance and energy recovery potential of five processes for municipal solid waste treatment

Hassan A. Arafat [a,*], Kenan Jijakli [a], Amimul Ahsan [b]

[a] Institute Center for Water and Environment (iWATER), Masdar Institute of Science and Technology, Abu Dhabi, United Arab Emirates
[b] Department of Civil Engineering and Institute of Advanced Technology, University Putra Malaysia, Selangor, Malaysia

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ABSTRACT

In this study, the environmental impacts were assessed for five municipal solid waste (MSW) treatment processes with energy recovery potential. The life cycle assessment (LCA) tool was used to quantify the environmental impacts. The five processes considered are incineration, gasification, anaerobic digestion, bio-landfills, and composting. In addition, these processes were compared to recycling where applicable. In addition to environmental impacts quantification, the energy production potentials for the five processes were compared to provide a thorough assessment. To maximize the future applicability of our findings, the analyses were based on the waste treatment technologies as they apply to individual waste streams, but not for a specific MSW mixture at a particular location. Six MSW streams were considered; food, yard, plastic, paper, wood and textile wastes. From an energy recovery viewpoint, it was found that it is best to recycle paper, wood and plastics; to anaerobically digest food and yard wastes; and to incinerate textile waste. On the other hand, the level of environmental impact for each process depends on the considered impact category. Generally, anaerobic digestion and gasification were found to perform better environmentally than the other processes, while composting had the least environmental benefit.

1. Introduction

Treatment and processing of municipal solid waste (MSW) should target minimizing the volume of landfilled waste whilst recovering as much resources out of it as possible. MSW is actually a resource with huge potential in terms of material and energy recovery. Thus, waste-to-energy operations have the advantages of resource generation and the minimization of landfilled waste. MSW is a heterogeneous resource that is a bundle of different waste types. The portion of each waste stream within the total amount of MSW differs according to several factors (Arafat and Jijakli, 2013). Waste streams that are classified as organic can be combusted or composted, whereas, waste streams that are classified as inorganic cannot. Organic waste streams include paper, plastics, textiles, wood, food wastes, and yard wastes; while the inorganic waste streams include glass and metals.

To fully understand the condition of MSW and its potential in energy generation, proximate and ultimate analyses are usually undertaken. The ultimate analysis of different MSW streams is presented in Table 1, which was obtained from two studies (Niessen, 2010; Themelis et al. 2002). Results of the proximate analysis are presented in (Niessen, 2010). While the analysis results will not be exactly the same for different countries, since MSW is a heterogeneous resource, a review of published results at various localities showed only slight discrepancies (Niessen, 2010; Themelis et al. 2002). Relative amounts of the MSW constituents in the MSW, on the other hand, can vary significantly by locality.

1.1. Waste-to-energy processes

Incineration is a direct combustion technology in which the feedstock is directly transformed into energy. Carbon dioxide and water vapor are the major compounds emitted through the incineration of MSW (Johnke, 2012). Additionally, the incombustible ash usually constitutes a concentrated inorganic waste that has to be disposed of properly.

Gasification is the process of converting organic compounds, under controlled oxygen flow, into a mixture of gaseous species that is dominated by carbon dioxide (CO_2), carbon monoxide (CO), hydrogen (H_2), and methane (CH_4). A summary of the products of gasification is given in Table 2 (Higman and van der Burgt, 2008).

* Corresponding author. Present address: Masdar Institute of Science and Technology, P.O. Box 54224, Abu Dhabi, United Arab Emirates. Tel.: +971 28109119.
E-mail address: harafat@masdar.ac.ae (H.A. Arafat).

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Table 1
Ultimate analysis of MSW streams as mass percentage of carbon (C), hydrogen (H), oxygen (O), nitrogen (N) and ash and the resulting chemical formula (Niessen, 2010; Themelis et al., 2002).

MSW category	% C	% H	% O	% N	% Ash	Chemical formula
Paper waste	43.41	5.82	44.32	0.25	6.0	$C_{3.6}H_{5.8}O_{2.8}N_{0.02}$
Plastic waste	60.0	7.2	22.8	0	10.0	$C_{5.0}H_{7.1}O_{1.4}$
Textile waste	55.0	6.6	31.2	4.6	2.4	$CH_{1.7}O_{0.7}N_{0.04}$
Wood waste	49.4	6.1	43.7	0.1	0.6	$C_{4.1}H_{6.1}O_{2.7}N_{0.007}$
Food waste	44.99	6.43	28.76	3.3	16.0	$C_{3.7}H_{6.4}O_{1.8}N_{0.2}$
Yard waste	40.31	5.64	39.0	2.0	13.0	$C_{3.4}H_{5.6}O_{2.4}N_{0.1}$

Table 2
Major products of gasification and the common health/environmental risks associated with those products (Higman and van der Burgt, 2008).

Product	Health/environmental hazard
Carbon dioxide (CO_2)	Green house gas
Methane (CH_4)	Potent green house gas but also a combustible fuel
Ammonia (NH_3)	Eutrophication
Hydrogen Cyanide (HCN)	Poisonous gas and explosive at high concentrations
Carbon monoxide (CO)	Toxic gas that causes asphyxiation. Also, a combustible gas
Hydrogen gas (H_2)	Explosive gas and combustible fuel. Can also cause asphyxiation

Anaerobic Digestion is used to treat organic waste with the ability to recover energy in the form of biogas (mainly methane) (Tchobanoglous et al. 2004). Residence times of anaerobic digestion reactors can be greater than 30 days (Tchobanoglous et al. 2004). However, an advantage of anaerobic digestion is that the process will produce less solid sludge than aerobic digestion (Henze et al. 2008).

In composting, organic waste is transformed aerobically into soil conditioners and water, with some emissions of NH_3 and CO_2 (Polprasert, 2007). In landfills, on the other hand, the organic fraction of MSW can decompose through an anaerobic digestion pathway, since the landfills are covered and void of large amounts of air, leading to biogas formation. Some landfills (usually termed bioreactor landfills) are designed and operated under conditions that will enhance biodegradation and biogas production (Davis and Cornwell, 2008).

1.2. Environmental impact and Life Cycle Assessment (LCA) of MSW treatment options

LCA is a cradle-to-grave analysis of the environmental impacts associated with a product or system. It analyzes all the stages in the life of the product/system including raw material extraction, production, usage, and disposal, focusing on the environmental impact of those stages. LCA's are now standardized through the ISO14000 standards (ISO, 2006a; ISO, 2006b). Impact assessment methods congregate different scientific methods and models to calculate the environmental impact. An example is the International Panel on Climate Change impact model (Pachauri and Reisinger, 2007).

Several LCA studies on MSW treatment are found in literature. A comprehensive summary of other LCAs found in literature is provided in Table 3 and in (Cleary, 2009). A major finding in most studies listed in Table 3 is that the production of energy or replacement of virgin materials associated with waste to energy and recycling technologies has tremendous environmental benefits over landfilling. In all the LCA studies on MSW encountered in literature, the focus was on applying the LCA methodology to assess specific MSW treatment scenario for a particular locality and as practiced in a given city with existing facilities. Hence, these studies have classically been too site specific. Yet, the analysis of waste management technologies from a technology centered perspective that extends beyond conditional location specific analyses could elucidate the true performance of those technologies.

The objective of this research work is to evaluate and compare different MSW treatment methods with energy recovery potential, from an energy, CO_2 footprint and environmental performance viewpoints. To generate the inventory for the LCA, energy generation from MSW was first modeled based on thermodynamic and process models. Next, this inventory was used for environmental

Table 3
A summary of literature on LCA studies on MSW management and treatment options.

Reference	Technology scope	Boundary	Conclusions/summary
(Aye and Widjaya, 2006)	Composting, and bio-landfill as compared to current open dumping	Waste from traditional markets in Indonesia	Bio-landfill had the least environmental impact and open dumping had the highest
(Beigl and Salhofer, 2004)	Recycling and landfilling	Selected area in Austria	A quantification of the environmental impact from recycling is compared to non-recycling. Recycling, ultimately has lower environmental impact
(Bjorklund and Finnveden, 2005)	A review of different case studies that compare recycling to landfilling and incineration	A review. Each reviewed case study is site specific and material specific	The paper confirms the environmental advantage of recycling and provides a quick review of major case studies
(Buttol et al. 2007)	Recycling, incineration composting and landfilling	Bologna district, Italy	Recycling and incineration have a clear environmental benefit
(Chaya and Gheewala, 2007)	Incineration and anaerobic digestion	Thailand	Anaerobic digestion performs better environmentally than incineration
(Eriksson et al., 2005)	Incineration, recycling, composting, and anaerobic digestion	Sweden	Differences between recycling, and incineration are small but in general recycling of plastic is somewhat better than incineration and biological treatment somewhat worse.
(Koroneos and Nanaki, 2012)	Recycling and anaerobic digestion	Greece	Paper recycling and anaerobic digestion of food waste is better than landfilling
(Moberg et al. 2005)	Recycling, incineration, and landfilling	Sweden	Recycling prevails as the treatment with most environmental benefit followed by incineration then landfilling
(Mendesa and Aramaki, 2004)	Incineration and landfilling	Sao Paolo, Brazil	Different incineration and landfill scenarios were compared but incineration performed better than landfilling
(Menikpura et al. 2013)	Integrated MSW management (including recycling and energy recovery)	Thailand	Materials recycling offers the largest reductions in GHG emission