

Life-Cycle Inventory of Municipal Solid Waste and Yard Waste Windrow Composting in the United States

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Abstract: This paper presents a life-cycle inventory (LCI) for solid waste composting. Three LCIs were developed for two typical municipal solid waste (MSW) composting facilities (MSWCFs) and one typical yard waste (YW) composting facility (YWCF). Municipal solid waste was assumed to comprise three organic components, food wastes, yard wastes, and mixed paper, as well as various inorganic components. Total costs, combined precombustion, and combustion energy requirements and 29 selected material flows—also referred to as LCI coefficients—were calculated by accounting for both the processes involved in originally producing, refining and transporting a material used in the facility as well as consumption during normal facility operation. Total costs ranged from \$15/t to \$50/t and energy requirements from 29 kw h/t to 167 kw h/t for a YWCF and a high quality MSW composting facility, respectively. More than 90% of the overall CO₂ emissions in all facilities were due to the biological decomposition of the organic substrate, while the rest was due to fossil fuel combustion.

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Introduction

Life-cycle assessment (LCA) can be used for the characterization and optimization of manufacturing processes or individual products. A life-cycle inventory (LCI)—part of a LCA—is the inventory of materials, energy requirements, and environmental emissions associated with a product or process from the time of the original recovery of raw materials used to build the product (“cradle”) to the time of its ultimate disposal to earth (“grave”) (Vigon et al. 1993).

Composting of the organic fraction of solid wastes is an aerobic biological stabilization process that can lead to the production of a soil amendment and/or could be used as a pretreatment technique prior to landfilling. Municipal solid waste (MSW) can be treated by composting, which is viewed as a recycling process. In 2000, 7.1% of the total solid waste generation was composted as yard wastes and food scraps (USEPA 2002). In addition, there were 3,800 yard waste composting programs and 15 mixed waste composting facilities in the United States during 2000, fewer than the 19 reported in 1999 (USEPA 2002).

There are three major types of compost processes including the “windrow,” “aerated static pile,” and “in-vessel” systems, with the former and the latter most dominant. Little is known

about the emissions during MSW composting, and energy requirements and costs are not thoroughly understood, depending highly on the MSW composting technology used. A database including theoretically derived environmental emissions during solid waste composting was presented by Hogg (2001). The environmental emissions presented in Hogg (2001) were based, however, on assumptions without the support of laboratory or full-scale measurements. A composting model (CoComposter) calculating costs for various composting processes was presented by Haith et al. (2001) without the inclusion of environmental emissions. The model focused on the composting of animal manure as the basic organic substrate with some MSW. Since, a model that would calculate costs, energy requirements, and environmental emissions during MSW composting did not exist, it was considered necessary to provide a tool that would include the calculation of all these parameters. The inclusion of all these parameters into a model can produce an integrated decision support tool that can give designers and policy makers the opportunity to improve and optimize their composting systems.

The goal of the work presented here was to develop cost estimates and to perform an inventory of energy requirements and selected environmental emissions (referred to as material flows here on) during composting of MSW and yard wastes. The model was designed to calculate LCI coefficients expressed in kilowatt hours and kilogram per (metric) ton of waste entering a MSW windrow composting facility. The model was based on laboratory experiments that were conducted to measure selected emissions for which there were no data available (Komilis and Ham 2000).

Model Development

The LCIs for solid waste composting were based on typical designs for two types of MSW composting facilities in the United States, one low quality MSW composting facility (LQCF) producing low quality compost and a high quality MSW composting facility (HQCF) producing high quality compost. In addition, a

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typical yard waste composting facility (YWCF) was designed. The LQCF produces a final product that can be used as landfill cover or can be directly landfilled in a “final storage” or “zero emission” landfill, while a HQCF and a YWCF can produce compost for use as a soil amendment. In the case of direct landfilling of the composted product, indirect benefits still exist, since waste volume reduction is achieved and a landfill with significantly reduced potential for emissions would probably require lower construction and monitoring costs compared to a typical MSW landfill.

Municipal solid wastes were assumed to comprise seven components of which three were organic (food waste, mixed paper, yard wastes) and four inorganic (plastics/refractory organics, glass, tin cans/aluminum, and other inorganics). The fractionation into three organic components was supported by laboratory work that studied the effect of mixtures of MSW components to the overall composting process (Komilis and Ham 2000).

The total cost, total energy requirements, and 29 selected material flows (i.e., environmental emissions) were calculated for each of the three facilities. The 29 material flows included several airborne and waterborne environmental emissions, as well as solid wastes, which are considered typical environmental pollutants and for which available data existed. The electricity and fuel (diesel) related energy requirements and environmental emissions were based on the USEPA (1991) and Dumas (1998). The functional management unit was designated to be 1t (wet) of MSW or yard waste of a specified composition entering the facilities (Weitz et al. 1999). Cost, energy, and material flows were expressed in \$/t, kW h/t, and kg/t respectively, which are hereafter referred to as LCI coefficients.

Composting Facility Designs

The process flow diagrams for the three types of facilities used in this study are shown in Fig. 1. Other design criteria for the three types of composting facilities used in the LCI are shown in Table 1. Designs were partly based on Taylor and Kashmanian (1988) and USEPA (1994) and are considered as typical United States windrow composting facilities.

The overall facility area comprised the tipping floor, treatment area (for trommeling and shredding), the composting pad, the curing area, buffer zone, offices, roads, and storage of reject material and equipment (Diaz et al. 1993). Design guidelines from compost windrow turner vendors literature were also used to calculate the composting pad area.

The composting pad was enclosed for both types of MSW composting facilities with a provision for ventilation by fans that continuously direct the air to an odor control system. The number of fans selected provides capacity to draw air from the enclosed composting pad as well as the tipping floor. A building height of 4.5 m was used and an air exchange rate of 12 times daily (every 120 min) was provided. Power requirements were based on Kong et al. (1996), who provided design parameters for a biofilter to treat styrene latent industrial emissions. The odor control system was assumed to operate 24 h/day.

Sewage sludge is sometimes added to MSW to increase their nitrogen and moisture contents. However, the addition of nitrogen is not a necessary condition for MSW composting to proceed and the addition of sewage sludge was not considered in this study. Yard wastes usually have enough nitrogen to allow for composting to proceed normally.

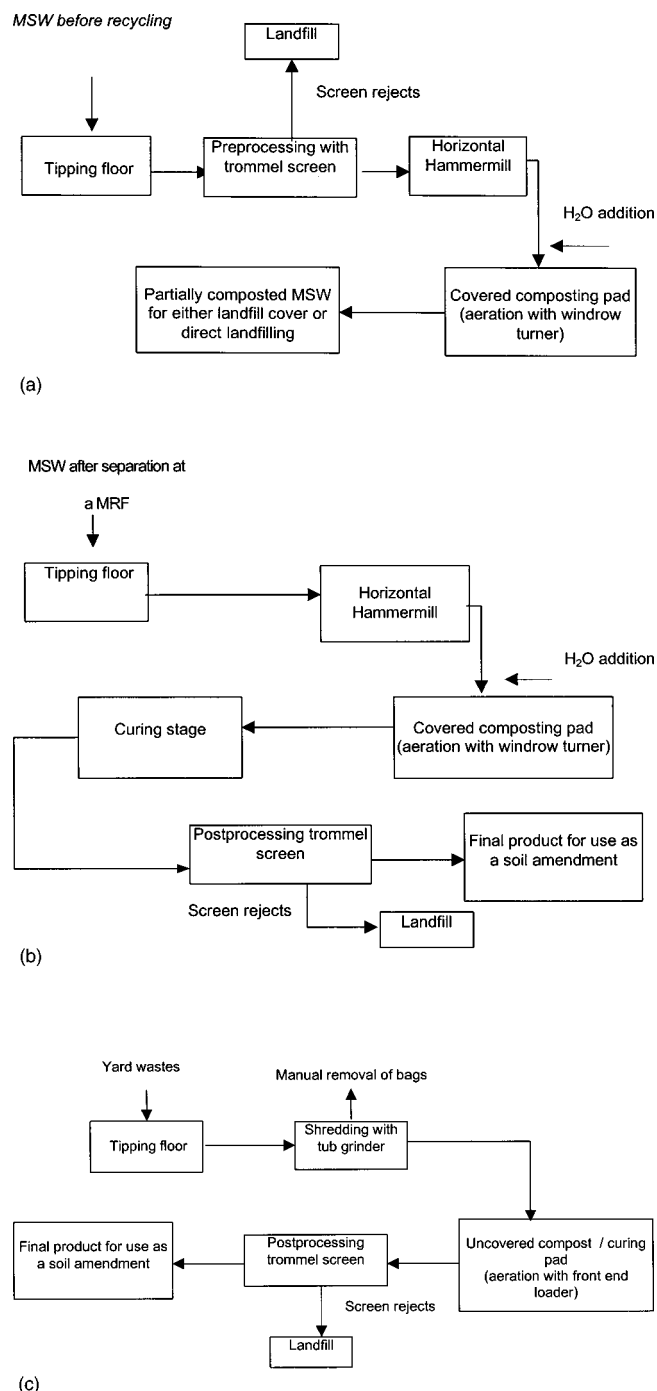


Fig. 1. Process flow diagrams for low quality municipal solid waste, high quality municipal solid waste and yard waste composting facilities

Mass Balance Approach

The facilities were designed for a typical MSW mixture before and after recycling for the LQCF and HQCF (Tchobanoglous et al. 1993), respectively, and for a yard waste mixture for the YWCF. The MSW composition (on a wet weight basis) before recycling was 42.2% mixed paper, 17.3% yard wastes, 8% food wastes, 11.3% plastics, 9.1% glass, 5.8% tin, and 6.3% aluminum. The MSW composition (on a wet weight basis) after recycling was 40% mixed paper, 18.5% yard wastes, 9% food wastes, 12% plastics, 8% glass, 6% tin, and 6.5% aluminum. Yard wastes were

Table 1. Design Criteria for Three Solid Waste Composting Facilities

Design parameters	Low quality CF	High quality CF ^a	Yard waste CF
Turning frequency	Once weekly	Three times weekly	Once monthly
Composting pad retention time	4 weeks	8 weeks	24 weeks
Odor/volatile organic compound control system	Yes	Yes	No
Curing retention time	0	4 weeks	Combined with composting time
Postscreening oversize fraction	0%	15%	5%
Buffer distance ^b	150 m	150 m	60 m

Note: CF=composting facility.

^aA materials recovery facility (not included in the life-cycle inventory) precedes the high quality composting facility to separate recyclable and compostable materials.

^bBuffer area is included in the overall facility area requirements.

assumed to comprise grass clippings and leaves at equal wet weights. A mass balance was performed for each waste component in MSW, as it flowed through the facility, by accounting for moisture contents, densities of the materials at different facility stages, screening efficiencies, and dry matter reductions during the composting process. Default values for several of the physicochemical properties of the MSW components and composted substrate were based on Alter (1983), Tchobanoglous et al. (1993), and Diaz et al. (1993).

According to the mass balance approach, 1 wet t of MSW will produce approximately 0.14 wet t of screen rejects in a HQCF and approximately 0.80 t of wet compost product.

Part-time use of equipment was allowed and a linear correlation of all design parameters to waste flow rate was implemented with an intercept. Therefore, a minimum number of units was assumed to exist for each type of facility, regardless of waste flow rate.

Life Cycle Inventory Boundaries

The LCI boundaries include all aspects of composting once waste is delivered and include compost final use (land application, landfill cover, soil amendment). All other activities and processes within those boundaries (transportation of vehicles within the facility, biodegradation process, etc.) are included in the LCI. Compost land application—when used—was assumed to be included in the overall LCI boundaries, since the environmental emissions produced after compost land application could still be an environmental burden and a result of the solid wastes originally entering the composting facility. Biologically induced emissions were calculated based on the extent of decomposition of the organic fraction of the waste, regardless of whether this level of degradation was reached within the facility or not. However, the transport of produced compost to its end use (land or landfill) was not included in the LCI. In addition, no cost, energy or environmental offsets from the potential marketing of the compost were accounted for, since compost does not normally fully replace a chemical fertilizer. It is noted that separate LCI models have been developed for the MRF that precedes the HQCF and for the landfill that accepts the LQCF produced compost material (Solano et al. 2002a, b).

Life Cycle Inventory Coefficients

Cost Coefficients

Cost coefficients include both capital (C) and operation and maintenance (O&M) costs. Capital cost includes the land purchase,

facility preparation and construction, and equipment purchase. It was amortized using a 15-year average design life for the facility as a whole and a 5% interest rate. Land acquisition and land development costs were partly based on Renkow et al. (1994). Other costs were provided by sales literature, equipment manufacturers, composting facility operators and literature, as referenced. The O&M costs included labor (Curtis et al. 1992), overhead, fuel consumption, electricity usage, and equipment maintenance. Table 2 presents default cost data used to develop the cost coefficients. The spreadsheet model was written so that all default values can be modified.

Energy Coefficients

Energy coefficients include the electrical energy requirements (EER) and diesel/gasoline fuel requirements. Electrical energy requirements include precombustion and combustion requirements. Precombustion EER are defined as the energy requirements for the mining, processing and transportation of the fuel used to produce 1 kw h of electricity, while combustion EERs include the energy content of the fuel required to produce 1 kw h of electricity. The average United States combined precombustion and combustion energy requirement for electricity is 3.06 kW h/kW h, with more than 98% of it being the combustion energy (Dumas 1998).

Diesel energy requirements were 12.6 kW h/L of diesel used, with 84% being the combustion energy based on United States average values (Dumas 1998). Table 3 shows selected energy requirements for some of the elements of the compost facilities.

Material Flows

The 29 material flows (MTFs) include airborne, waterborne, and solid environmental emissions related to energy consumption within the facility. In addition, MTFs include the major gaseous environmental emissions (CO₂, NH₃) produced biologically during the composting process. Material flows were categorized as precombustion material flows and combustion material flows and as fossil related and biomass related material flows. Precombustion material flows reflect the environmental emissions produced in the mining and transportation process required to provide the fuels (diesel) or electricity used during the operation of the composting facility. Combustion material flows are produced due to the combustion of fuel for equipment or electrical energy generation. Fossil MTFs are produced due to the combustion of fossil fuels (such as coal, natural gas, residual and distillate oil), while biomass related MTF are produced by the combustion of nonfossil fuels (e.g., wood) or from the biodegradation of organic matter.

Table 2. Capital (C), Operating (O) and Maintenance (M) Costs for Three Types of Solid Waste Composting Facilities^{a, b}

Item/equipment	Cost (\$/unit)
Paving	\$180,000/ha ^c
Grading	\$12,500/ha ^c
Fencing	\$23/m ^c
Land acquisition	\$3,100/ha ^c
Office cost	\$430/m ^{2d}
Front end loader	C: \$150,000 ^e M: \$1,000/year
Screens	C: \$100,000 ^e M: \$500/year
Tub grinder	C: \$180,000 ^e M: assumed same as hammermill's
Odor control system	C: \$1,3 per m ³ of air/day ^f M: \$500/year
Hammermill	C: \$250,000 ^e M: \$0.741/t ^g
Compost pad building (includes paving with tar)	\$70/m ^{2h}
Windrow turner	C: \$180,000 M: \$22/h ⁱ
Diesel	O: \$0.32/L ^j
Electricity	O: \$0.075/kW h ^j
Labor and overhead cost	\$8/h equipment operator; (overhead taken as 40% of labor cost)

^aCosts shown are default values adjusted to 1999.^bEngineering cost was taken as 15% of construction cost, while equipment installation cost was taken as 30% of equipment capital cost.^cRenkow et al. (1994).^dUSEPA (1991).^eTchobanoglous et al. (1993).^fKong et al. (1996) refers to a sorption unit containing activated carbon, soil and woodchips.^gDiaz et al. (1982).^hPersonal communication with plant operator(s).ⁱCompost turners' sales literature.^j1999 values.**Table 3.** Energy Requirements for Major Equipment in Three Types of Solid Waste Composting Facilities

Equipment	Number of units/t/day	Energy requirements
Windrow turner	0.17 ^a	0.13 kW h/t ^b
Hammermill	0.0029	15 kW h/t ^c
Trommel screens	0.0025	1.1 kW h/t (precomposting) 0.8 kW h/t (postcomposting) ^d
Tub grinder	0.0038	10.2 kW h/t ^e
Front end loader	0.003	112 kW/unit ^f
Odor control system	Correlation of air flow rate to cost and energy	5 × 10 ⁻⁵ kW/m ³ of air/day ^g
Building operation	Correlation of area units to cost and energy	320 kW h/m ² /year (office) ^h

Note: The windrow turner, tub grinder, and front end loader are run on diesel while all other equipment are run on electricity.

^aThe coefficient shown was calculated by accounting for the area of the composting pad and the turning frequency.^bCompost turner sales literature.^cThe energy requirement given is multiplied by certain coefficients to account for the nature of wastes (raw or presorted wastes) and the energy necessary to reach a final product size of 5 cm (Tchobanoglous et al. 1993).^dDiaz et al. (1982).^eTub grinder sales literature.^fFront end loader sales literature.^gKong et al. (1996)^hDOE (1992, 1994).

Table 4. Fossil (Diesel) Fuel Combustion Material Flows from Selected Diesel Powered Equipment

Type of vehicle	Diesel consumption (L/t MSW) ^a	HC ^b (kg/kJ)	CO (kg/kJ)	NO _x (kg/kJ)	PM _{total} (kg/kJ)	SO _x (kg/kJ)	CO ₂ (kg/L diesel)
Front end loader (values refer to a tracked loader)	0.40	2.6E-7	8.9E-7	3.6E-6	2.5E-7	3.1E-7	2.8
Tub grinder (values refer to a chipper/stump)	1.3	4.7E-7	1.9E-6	3.1E-6	3.1E-7	3.6E-7	2.8
Windrow turner	0.90 ^c	8.3E-7	2.6E-6	3.9E-6	0.0E+0	0.0E+0	2.8

Note: Source (USEPA 1991); and MSW=municipal solid waste.

^aDiesel consumption was calculated using the power usage (in kilowatts) required by each type of equipment in the facility and a consumption coefficient equal to 0.13 L of diesel/h/kW, as suggested by pertinent sales' literature.

^bHC=total exhaust and crankcase hydrocarbons including aldehydes.

^cThe value given refers to a high quality composting facility. This value is equal to 0.1 for a low quality composting facility due to reduced turning frequency.

This categorization was performed, since biomass related CO₂ is given a weighting factor of zero in calculation of greenhouse equivalents (Vigon et al. 1993). This is because biodegradation related CO₂ is continuously produced and consumed within a relatively short period of time, while fossil fuel related CO₂ is introduced into the global atmosphere after the combustion of organic material that was stored over geologic time. Fossil and nonfossil MTFs may belong to either the precombustion or combustion categories.

Table 4 shows six diesel fuel combustion material flows for selected equipment. Environmental emissions associated to electrical energy usage have been presented in Dumas (1998) and are United States average values. Table 5 includes all 29 material flows used throughout this study.

Biodegradation Induced Gaseous Material Flows

Carbon dioxide (CO₂), ammonia (NH₃) were considered to be the main gaseous compounds produced during the composting of wastes and were therefore measured during laboratory experiments presented in Komilis and Ham (2000). N₂O, a major greenhouse gas, was not measured due to analytical constraints. The experiments were performed to estimate these emissions from mixtures of three organic MSW components (food wastes, mixed paper, and yard wastes) and were based on a mixture experimental design approach to also evaluate the interactions among components in a solid waste mixture (Komilis and Ham 2000).

Experiments extended until basically "complete" degradation was reached, as measured by the CO₂ flow rate and after ensuring that this was not due to moisture limitations. The experiments were conducted under aerobic conditions and measurements of the headspace gaseous composition revealed that methanogenic conditions did not occur. This generally simulates the conditions in actual MSW composting facilities, since, even if anaerobic conditions do develop in the center of the piles, the anaerobic gases emitted would be oxidized at the surface of the piles. Nitrogen was added prior to the initiation of the experiments to achieve a C/N ratio of around 30. This is sometimes done in practice with the addition of N rich substrates (such as sewage sludge) to MSW prior to composting.

As a result of the experimental work the following equations were derived for CO₂ and NH₃ emissions and for the reduction in the dry matter (Komilis and Ham 1999)

$$YCO_2 = 220 \cdot (\pm 19)F_P + 240 \cdot (\pm 21)F_Y + 370 \cdot (\pm 24)F_F \quad (1)$$

$$YNH_3 = 1.3(\pm 1.4) \cdot F_P + 5.2(\pm 1.4) \cdot F_Y + 38(\pm 1.6) \cdot F_F - 69(\pm 23) \cdot F_P \cdot F_F \quad (2)$$

$$DR = \frac{YCO_2}{490(\pm 18)} \quad (3)$$

where YCO₂=CO₂ yield (in g C/dry kg of the organic fraction of MSW); YNH₃=mass of NH₃ (in g N/dry kg of the organic fraction of MSW); and DR=dry weight reduction of the organic fraction of MSW (expressed as a fraction); F_P, F_Y, and F_F=dry fractions of mixed paper, yard waste, and food waste, respectively, in the mixture, with each of the F_P, F_Y, F_F values ranging from 0 to 1 and with F_P+F_Y+F_F always equal to 1. Values in parentheses are the standard errors of the corresponding coefficients.

Leachable and Other Waterborne Material Flows

Generally, varying amounts of leachate can be produced in MSW and yard waste composting facilities starting from 0 (Metcalf et al. 1997, Krogmann and Woyczehowski 2000) to approximately 490 L/t (Krogmann et al. 2000). The limited data on leachable material mass loadings presented in Cole (1994) and Krogmann and Woyczehowski (2000) cannot be transformed to the format required in this LCI (kilogram of material/ton of MSW entering the facility). Data on the leachable emission after MSW compost land application have been presented by Christensen et al. (1983a,b, 1984a,b), who performed lysimeter experiments to determine leachate characteristics and quantities of MSW derived compost. The data from Christensen were given on a per unit mass basis of dry MSW derived compost and are highly depended on soil properties, vegetation, and other environmental conditions. Given the limitations in the available data, this aspect of leaching emissions from MSW and yard wastes during and after composting was not included in this LCI. The LCI includes, however, all waterborne emissions associated with diesel and electricity precombustion and combustion processes.

Allocation of Cost, Energy and Material Flows to Municipal Solid Waste Components

All LCI parameters presented in this paper were equally allocated to all individual MSW components, since MSW will be always entering the facility as a mixture in a mixed MSWCF. Therefore, if the cost of the facility is \$x/ton of MSW entering the facility, then the cost of treating 1 ton of any waste component, organic or inorganic, will also be \$x. This was done, since it was assumed that all components will always be a part of a MSW mixture.

Table 5. Life Cycle Inventory (LCI) Costs, Energy Requirements and material flows (pollutants) for 100 t/day Municipal Solid Waste and Yard Waste Composting Facilities (CF)

LCI coefficients	Low quality CF	High quality CF	Yard waste CF
Total cost (dollars/t)	28 ^a	49 ^b	16 ^c
Total energy requirements (kW h/t)	97 ^d	167 ^e	29 ^f
Airborne material flows (kg/t)			
PM _{total}	3.8E-02	6.0E-02	1.8E-02
NO _x	1.4E-01	2.9E-01	1.6E-01
HC(non CH ₄)	2.3E-02	5.9E-02	3.5E-02
SO _x	1.9E-01	3.1E-01	3.5E-02
CO	4.5E-02	1.2E-01	8.2E-02
CO ₂ biomass ^g	2.5E+02	3.9E+02	3.5E+02
CO ₂ fossil	2.2E+01	3.7E+01	7.3E+00
NH ₃ ^h	3.7E-01	5.0E-01	2.5E+00
Pb	1.3E-09	2.8E-09	2.3E-09
CH ₄	1.4E-04	2.3E-04	2.3E-05
HCl	1.4E-07	3.0E-07	2.5E-07
Waterborne material flows (kg/t)			
Dissolved solids	1.2E-02	2.6E-02	2.1E-02
Total suspended solids	1.1E-05	2.4E-05	2.0E-05
BOD ₅	1.2E-05	2.6E-05	2.1E-05
COD	5.9E-05	1.3E-04	1.0E-04
Oil	1.6E-04	3.3E-04	2.5E-04
H ₂ SO ₄	1.5E-02	2.5E-02	1.5E-03
Fe	3.8E-03	6.3E-03	3.7E-04
NH ₃	1.7E-06	3.6E-06	2.9E-06
Cu	0.0E+00	0.0E+00	0.0E+00
Cd	0.0E+00	0.0E+00	0.0E+00
As	0.0E+00	0.0E+00	0.0E+00
Hg	0.0E+00	0.0E+00	0.0E+00
PO ₄ ⁻³	0.0E+00	0.0E+00	0.0E+00
Se	0.0E+00	0.0E+00	0.0E+00
Cr	3.0E-09	6.9E-09	6.9E-09
Pb	1.8E-09	3.8E-09	3.1E-09
Zn	2.6E-08	5.7E-08	4.5E-08
Solid waste (miscellaneous) ⁱ	2.6E+00	4.3E+00	2.6E-01

^aCapital cost is 58% and operation and maintenance (O&M) cost is 42%.

^bCapital cost is 72% and operation and maintenance (O&M) cost is 28%.

^cCapital cost is 34% and operation and maintenance (O&M) cost is 66%.

^dDiesel precombustion and combustion account for 1 and 5%, respectively, of the total energy requirements, while the rest is accounted for by electricity precombustion and combustion energies.

^eDiesel precombustion and combustion account for 2 and 8%, respectively, of the total energy requirements, while the rest is accounted for by electricity precombustion and combustion energies.

^fDiesel precombustion and combustion account for 11 and 60%, respectively, of the total energy requirements, while the rest is accounted for by electricity precombustion and combustion energies.

^gIncludes amounts of CO₂ produced due to the biodegradation process within the composting facility.

^hIncludes amounts of NH₃ produced due to the biodegradation process within the composting facility.

ⁱDoes not include screen rejects and is associated with precombustion and combustion emissions.

All airborne and waterborne material flows, excluding the biologically induced CO₂ and NH₃, are a function of total energy and were therefore also equally allocated to all MSW components. The biomass related CO₂ and NH₃ material flows were calculated separately for each organic waste component using Eqs. (1) and

(2), while the inorganic components did not produce any CO₂ or NH₃.

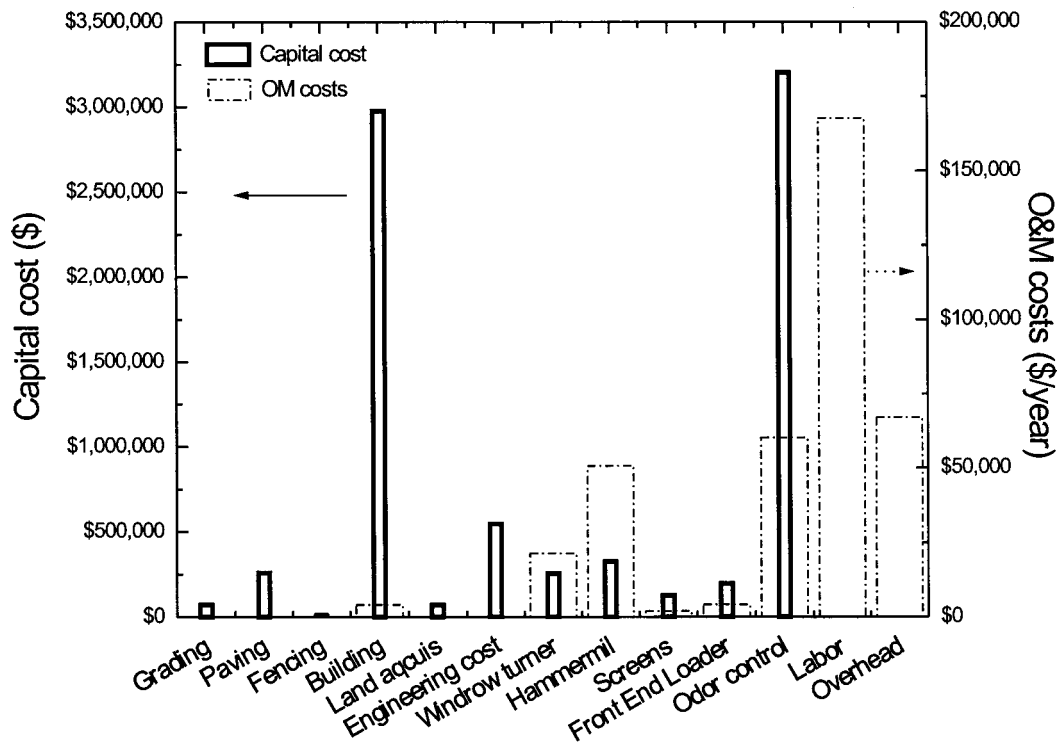


Fig. 2. Capital and operation and maintenance cost breakdown for typical 100 t/day high quality municipal solid waste composting facility

Results and Discussion

Life Cycle Inventory Model Results

The LCI models were run using typical United States MSW compositions separately for the LQCF and HQCF. A typical YW mixture was used for the YWCF. An input flow rate of 100 TPD (t/day) was used for all three facilities. Table 5 presents the predictions of the LCI model for each of the three composting facilities using the default data presented in Table 2. Each material flow is the sum of all flows of that material present in various streams or processes. All LCI model results are point estimates and no data variability was included.

Table 5 shows that the least expensive facility is the YWCF, with a total cost of \$16/t. This value is within the range actual total costs of yard waste composting facilities in the United States, as reported by Steuteville (1996). According to Steuteville (1996), total costs for seven yard waste composting facilities in the United States range from \$8/ton, for a facility with no shredding and screening, to \$26/ton, for a facility that utilizes open air windrows with turning.

The total costs for the LQCF and HQCF are \$28/ton and \$49/ton, respectively. Differences are primarily due to the larger retention time of the HQCF compared to LQCF, which results in a larger composting pad and therefore a higher cost for the compost pad building and odor control. In addition, the prescreening step in the LQCF removes approximately 30% of the waste, which is therefore neither shredded nor composted, reducing overall cost. According to Renkow and Rubin (1998), total costs for MSW composting facilities range from \$35/ton to \$54/ton (MSW processed). Values reported are based on seven United States MSW composting facilities with an average total cost of \$53/ton. Differences in the designs of the actual facilities with the "typical" design used here are expected. Several facilities use in-vessel systems, which are generally more expensive than fa-

cilities that utilize windrow turners; however, model predictions are comparable to costs of operating United States composting plants.

The capital cost accounts for 58 and 72% of the total cost for the LQCF and the HQCF, respectively, while it accounts for 34% of the total cost of the YWCF. According to Renkow and Rubin (1998), 48% of the total cost is capital (or debt) cost based on averaging from the reported data.

Total energy requirements shown in Table 5 are the sum of electrical and diesel precombustion and combustion energies for each facility and are expressed in kilowatt hour/ton. Total energy of the YWCF is much less than the energy from the LQCF and HQCF, primarily because there is no odor control system. The HQCF energy requirements are approximately twice than that from the LQCF. This is primarily due to the larger odor control system. In addition, removal of about 30% of the incoming material during prescreening in the LQCF results in even lower total energy requirements than that of the HQCF in which no prescreening is used. According to Diaz et al. (1986), average energy requirements in a MSW composting facility are 34.4 kW h/t of MSW. The values predicted by the model are 97 kW h/t and 167 kW h/t, for the LQCF and HQCF, respectively. The higher values are partially because precombustion and combustion energy requirements are both included in the total energy requirements. The values by Diaz et al. (1986) refer to energy consumed directly within the facility, including extensive preprocessing prior to composting (e.g., size reduction, screening). In addition, no odor control system is included in the values used by Diaz et al. (1986).

The atmospheric pollutants, excluding CO₂ (biomass) and NH₃, are primarily a function of the energy usage and energy distribution. All energy related atmospheric emissions are higher for the HQCF than the LQCF. This reflects electricity and diesel requirements for each facility. In the case of the YWCF, the

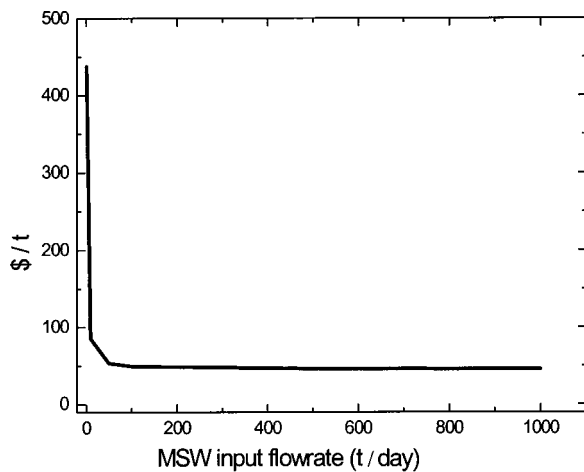


Fig. 3. Economy of scale for high quality municipal solid waste composting facility (Note: Total cost includes capital cost and operating/maintenance cost based on 5% interest rate and 15 year design life)

HC, CO, and NO_x material flows are similar to the values for the LQCF. This is a result of the higher usage of diesel in the YWCF compared to the MSW facilities, although total energy is less for the YWCF than both MSW composting facilities. The CO_2 (biomass) and NH_3 values were calculated from Eqs. (1) and (2), respectively, and refer to the gases produced due to substrate decomposition. The relatively low ammonia emission for the LQCF is due to the high percentage of paper contained in the MSW entering the composting pad. A higher percentage of yard wastes and food wastes is entering the composting pad at the HQCF, as some paper is removed in the MRF prior to composting. The higher food and yard waste concentrations contribute to the higher ammonia flows in the HQCF.

Breakdown of Costs, Energy, and Material Flows

The breakdown of the capital and O/M costs is presented in Fig. 2 for a 100 TPD HQCF. Relative responses were the same for both MSW facilities and therefore the results for the HQCF are only shown. The composting pad building and the odor control system account for approximately 77% of the total capital cost. Building cost is primarily due to construction of the composting

pad, while the office and storage building account for only 10% of the total building cost. Engineering, hammermill and the loader costs are next highest.

Combined labor cost and overhead costs account for approximately 62% of the total operating cost. Electricity and diesel related costs rank next highest with 29% of the total operating cost. Of the total electricity cost, 62% is required for the odor control operation, while the remaining 38% is mostly due to hammermill operation. Maintenance costs for the hammermill and windrow turner are less than 10% of the total operating cost, while it was assumed that maintenance costs for the front end loader, the screens and the odor control system are \$1,000, \$500, and \$500, respectively.

A typical economy of scale for a HQCF is shown in Fig. 3. As shown, composting for a HQCF is affected by economy of scale for facilities with a solid waste tonnage less than approximately 80 TPD. For mass input flow rates greater than 80 TPD, the unit costs range between \$45 and \$49/ton.

Based on the HQCF, 29, 56, 3, 7, and 1% of the total energy requirements are due to hammermill, odor control, front end loaders, windrow turner, and trommel screen operation, respectively, while 4% is due to building operation. Relatively similar values apply to the LQCF. In the case of the YWCF, 55, 16, 8, and 21% of total energy are due to the tub grinder, the front-end loader, screens and building operation, respectively.

In the LQCF and HQCF, electricity related energy accounts for more than 90% of the total energy with the rest being diesel-derived energy. In the YWCF, 60% of the total energy is diesel combustion energy with 29% being electricity and the rest being diesel precombustion energy. This is because only diesel-powered equipment is used in the YWCF and electricity is limited to the building operation.

Table 6 presents the fractions and the absolute amounts of selected airborne material flows (atmospheric pollutants) attributed to diesel combustion. The percentages of the pollutants shown in Table 6 are produced within the boundaries of the facility itself. Due to the extensive usage of electricity in the LQCF and HQCF diesel combustion is responsible for less than 50% of all the emissions shown in Table 6 with the exception of CO. This is explained by the fact that windrow turning—which relies on diesel—is done more frequently in the HQCF compared to the LQCF. Diesel combustion is generally responsible for production of a relatively large percentage of the NO_x and CO emissions from both the MSW composting facilities. SO_x emissions are primarily produced due to electricity consumption and are therefore

Table 6. Fraction of Atmospheric Pollutants Attributable to Direct Diesel Combustion within Boundaries of Composting Facilities^a

Facility type	PM_{total}	NO_x	HC	SO_x	CO	CO_2 (fossil)
MSW LQCF	7% (0.0026) ^b	37% (0.052)	23% (0.005)	2% (0.0034)	37% (0.017)	6% (1.3)
MSW HQCF	4% (0.0026)	49% (0.14)	42% (0.024)	1% (0.0034)	61% (0.077)	10% (3.6)
YWCF	79% (0.014)	94% (0.15)	58% (0.019)	46% (0.016)	96% (0.078)	64% (4.6)

Note: Source (Dumas 1998); MSW=municipal solid waste; LQCF=low quality composting facility; HQCF=high quality composting facility; and YWCF=yard waste composting facility.

^aThe rest is due to diesel precombustion and electricity precombustion/combustion emissions.

^bValues in parentheses are absolute values in kg/t MSW or yard waste.

Table 7. Sources of Selected Airborne Material Flows from Day 100 t/day High Quality Municipal Solids Waste (MSW) Composting Facility

Material	Diesel precombustion (kg/t MSW)	Diesel combustion (kg/t MSW)	Electrical energy precombustion and combustion (kg/t MSW)
PM _{total}	0.0E+00	0.3E-03	5.7E-02
NO _x	1.0E-03	1.4E-01	1.5E-01
HC	1.0E-02	2.5E-02	2.4E-02
SO _x	1.0E-03	3.0E-03	3.1E-01
CO	1.0E-03	7.6E-02	4.8E-02
CO ₂ (fossil)	5.6E-01	3.6E+00	3.3E+01

Note: Source: USEPA (1991); and Dumas (1998).

produced outside the boundaries of the facility itself. Because of the limited use of electricity in the YWCF, the majority of the atmospheric emissions are due to diesel combustion.

Table 7 shows the contribution of diesel precombustion, diesel combustion and combined electricity precombustion and combustion to the selected gaseous emissions resulting from the operation of a high quality MSW composting facility at 100 TPD. Electricity precombustion and combustion is primarily responsible for the emissions of the largest fraction of fossil-fuel related emissions. Approximately 90% of the overall fossil CO₂ emitted from the aforementioned facility—i.e., approximately 33 kg CO₂/t MSW—is a result of electrical usage. However, 92, 91, and 98% of the overall CO₂ emissions from the LQCF, HQCF, and YWCF, respectively, are due to the decomposition of the organic substrate. Essentially all of the ammonia emitted from all facilities is due to decomposition.

Sensitivity Analysis

Table 8 presents a sensitivity analysis for the key design parameters of a LQCF. The base case was an input waste flow rate of 100 TPD. To perform the sensitivity, a 50% change in the selected parameter was specified and the change from the baseline output value was recorded as a percentage. The change was recorded for

total cost, total energy and the NO_x flow. Other air pollutants (airborne material flows) are also proportional to power.

As Table 8 shows, retention time, odor control air exchange rate and labor salaries have the greatest effect on total cost. The retention time and odor control also have the largest effect on energy and material flows. Interest rate and design life have the next largest effect on total cost. Composting pad cost has also a relatively large effect on total cost, but has no effect on energy and material flows.

Hammermill design has a marked effect on total energy and emissions, since it accounts for a large usage of electrical energy. The use of presorting will affect the shredding coefficient by changing it from 1 to 0.67, corresponding to raw and sorted wastes respectively, resulting in reductions in total energy usage and gaseous environmental pollutants.

It also appears that windrow geometry affects total cost, energy and material flows. A higher windrow height than the one used as the default value will result in a smaller composting pad for the same mass of wastes entering the pad. Windrow geometry however is limited by the type of turning equipment used and can also affect oxygen content in the piles. Therefore, windrow geometry can have an impact on the odorous compounds produced, but this is not accounted for in the LCI model. Buffer distance,

Table 8. Sensitivity Analysis on Selected Parameters Using 100 t/Day as Baseline

Parameter	Base case	Adjusted value	Change in total cost (%)	Change in total energy (%)	Change in NO _x ^a (%)
Grading cost (\$/ha)	12,500	18,750	0.2	0.0	0.0
Paving cost (\$/ha)	180,000	272,000	0.7	0.0	0.0
Land acquisition cost (dollars/ha)	3,100	4,650	0.3	0.0	0.0
Composting pad building cost (\$/m ²)	70	105	9.5	0.0	0.0
Interest rate (%)	5%	7.5%	10.1	0.0	0.0
Facility design life (years)	15	22.5	-12.7	0.0	0.0
Wages (\$/h)	8	12	16.1	0.0	0.0
Number of employees	10	15	16.1	0.0	0.0
Turning frequency (No./week)	1	1.5	0.2	0.7	0.06
Retention time (days)	30	45	18.5	16.1	16.3
Buffer distance (m)	150	230	0.7	0.0	0.0
Odor control air change rate (min)	120	80	12.4	18.8	20.2
No odor control system	Present	Absent	-24.8	-37.7	-40.4
Compost windrow height (m)	1.8	2.7	-12.6	-10.6	-11.1
Change of hammermill shredding coefficient (raw and presorted waste)	1.0 (Raw)	0.67 (Presorted)	-1.5	-17.4	-18.3

^aOther pollutants (material flows) are similarly proportional to energy requirements except CO₂ biomass and NH₃.

grading cost, paving cost and turning frequency have minor effects on the total cost. The absence of an odor control system reduces total cost, energy, and material flows by more than 25% and is therefore considered a significant part of the composting facility.

Practical Application of Results

The results of the LCI presented here may be used to compare the environmental performance of other MSW management processes to alternatives that include composting. This model has also been used to evaluate optimal strategies for solid waste management as described by Solano et al. (2002a,b).

In addition, the sensitivity analysis performed above aids in the optimization of several design aspects within the composting facility itself. For example, the use of an odor control system had a major effect on cost, energy requirements, and environmental emissions. Changes in the odor control system or alternative ways to control odors could significantly aid in the reduction of the costs, energy requirements and environmental emissions of the composting process. Thus, the LCI process can be used to identify the aspects of the operation for which improvement will result in the most benefit.

Summary

1. Total costs for the LQCF, HQCF, and the YWCF are approximately \$30/t, \$50/t, and \$15/t, respectively, for 100 TPD facilities, which are comparable to total costs of actual MSW and yard waste composting facilities in the United States.
2. The odor control system appears to be the largest capital cost. In particular, the odor control system and the building (primarily the enclosed composting pad building) comprise approximately 77% of the total capital cost combined, for the MSW composting facilities, followed by the engineering cost and equipment cost.
3. Total energy requirements are 97, 167, and 29 kw h/ton for the LQCF, HQCF, and YWCF, respectively.
4. Approximately 90, 8, and 2% of the total energy requirements are due to electricity precombustion/combustion, diesel combustion, and diesel precombustion, respectively, for the HQCF.
5. Compost retention time and odor control air exchange rate are the factors that most affect cost, energy and gaseous emissions. Energy requirements are sensitive to the type of wastes (raw or presorted) handled by the hammermill and windrow geometry.
6. More than 90% of the emitted CO₂ is due to solid waste decomposition (CO₂ biomass).

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EPA; no official endorsement should be inferred.

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