

Environmental Life Cycle Assessments of Decentralized Municipal Solid Waste Management: A Novel Waste-To-Compost Approach

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Abstract

Global waste generation is increasing rapidly in parallel with population growth and rapid urbanization leading to municipal solid waste management challenges. Most of the underdeveloped or developing countries encounter crucial challenges in adopting the best waste management practices in the face of climate change and environmental stewardship. This study has examined the environmental impacts of domestic organic waste generated at the Dhaka North City Corporation in Bangladesh—a rapidly growing country in its population and economy. This study conducted environmental life cycle assessments of decentralized municipal solid waste management strategies in comparison with the conventional landfilling options using a waste-to-compost approach. Four major waste management scenarios were compared; the conventional windrow composting (S1), proposed automated composting with EP-1000 machine (S2), and the current practices of sanitary (S3) and unsanitary (S4) landfilling. Environmental Life cycle assessment (ELCA) of the four scenarios were conducted using Open LCA software for their environmental impact categories namely global warming potential (GWP100), freshwater aquatic ecotoxicity potential (FAETP), human toxicity potential (HTP), and terrestrial ecotoxicity potential (TEP). The impacts analyzed were based on the level of greenhouse gas (GHG) emissions from each process and one ton of municipal solid waste as a functional unit. Results revealed that the four impact categories for the proposed decentralized waste to compost process scenarios (S1 and S2) were lower than those of the conventional landfill scenarios (S3 and S4). The overall quantity of total yearly GWP100 from decentralized compost facility of S1 (1.14 million Mg CO₂-eq Mg⁻¹) and S2 (411 kg CO₂-eq Mg⁻¹) were multifold lower than emissions from conventional landfilling of S3 (~2.12 million Mg of CO₂-eq Mg⁻¹) and S4 (~3.87 million Mg of CO₂-eq Mg⁻¹) scenarios reflecting the environment-friendly outcome of the former than the latter scenarios. Similar trends of lesser quantities of FAETP, HTP, and TEP were noticed depicting the S1 and proposed S2 scenarios as better options than conventional landfill of S3 and S4 scenarios. The study concludes that sustainable solid waste management through decentralized composting can substantially reduce GHG emissions, freshwater aquatic ecotoxicity, human toxicity, and terrestrial ecotoxicity potentials over the life cycle of municipal waste production when compared to relevant disasters from landfilling. In conclusion, the development of decentralized waste-to-compost facilities in Dhaka or other similar units across the globe can prove a better and more sustainable waste management strategy with a greater potential to mitigate adverse impacts of climate change and environmental pollution.

Keywords: life cycle assessment; greenhouse gas emission; environmental pollution; composting; sustainable solid waste management

Introduction

Management of municipal solid waste (MSW) is an emerging challenge exhibited in developing countries, facing accelerated urban population growth, unplanned urbanization, and industrialization (Menikpura et al. 2012). World Bank defines MSW as waste from domestic, commercial, industrial, and other processes involving municipal services. The World Bank estimates that global waste generation will increase from 2.01 billion tonnes in 2016 to 3.40 billion tonnes in 2050 (Kaza et al. 2018). Release of toxic pollutants including greenhouse gas (GHG), and particulate matter into the air, as well as other

pollutants in water and soil, are very common from a typical unsanitary landfill. Several health impacts, such as respiratory and cardiovascular disease, and adverse birth impacts are associated with exposure of these particles (Sharma 2016). In 2016, an estimated 1.6 billion tonnes of carbon dioxide equivalent (CO₂-eq) GHG emissions directly resulted from MSW, representing approximately 3.2% of global emissions (Giroto et al. 2015). These emerging environmental problems bring out the importance of the MSW management challenges (Eren 2019).

Bangladesh is a fast-growing developing country in Southeast Asia. Dhaka, the capital city of Bangladesh

is one of the most densely populated cities in the world (World Bank 2018) and currently ranks the world's eleventh largest megacity with a population of 25 million living in an area of 1528 km². This city profile traces the trajectories of its urban development to becoming a megacity and characterizes its emerging challenges due to informal urbanization and climate change impacts. The waste generation in Dhaka is also rapidly rising (Alam and Qiao 2020). The main activities in waste management functions have been the collection, transportation, and open dumping of waste in landfills. The waste volume during the period between 2017-2018 and 2021-2022 increased tremendously from around 1.05 million tonnes to 1.20 million tonnes yearly. This suggests that from 2015-2020, Dhaka City Corporation (DCC) might have managed over 5.6 million tonnes of waste, dominantly organic contents (Waste Concern 2014). MSW in Dhaka is characterized by a high organic matter fraction in the range of 60-80% on a wet basis (Menikpura et al. 2012; Alam and Qiao 2020). DCC is the main responsible authority to manage Dhaka's MSW within a service area of around 360 km² (JICA, 2005). Waste generated, initially stored at the households, are primarily transported to the secondary storage locations such as dustbins, container, and secondary storage points called secondary transfer station (STS) installed by DCC. This primary collection and transportation are provided by either non-government organizations (NGOs), community-based organizations, or DCC deployments. The secondary transportation to the final treatment site is solely operated by DCC (JICA, 2005). There are currently two major landfill sites for Dhaka's MSW and no site has complete sanitary facilities, although there are plans to provide such facilities shortly (Bangladesh Database 2014). Few studies have examined diverting MSW in Dhaka to lessen the environmental burden of waste in landfills (Bangladesh Database 2014). Bahauddin and Uddin, (2012) have focused on community-level engagement in MSW. Hasan et al. (2009) in his study highlighted the demand for landfill sites. No formal approach from the DCC level is available to segregate the waste into recyclable and non-recyclable components. However, informal waste pickers collect recyclable wastes from the dustbins/containers and landfill sites and sell those to either petty traders or wholesalers (Yasmin and Rahman 2017). Around 40 - 60% of waste remain uncollected due to the absence of awareness, motivation, expertise, and budget (Ahsan

et al. 2014). In 2010, a strategy was adopted by the government of Bangladesh namely, the 'National 3R (Reduce, Reuse, Recycle) Strategy' to implement waste reduction measures and ensure sustainability in waste management (Centre for Clean Air Policy 2015).

According to the World bank report (What a Waste 2.0, World Bank), globally many countries are considering sustainable development as a basis for implementing any development activity. Sustainable development is a continuous process that aims to achieve balance among three main components of development; social, environmental, and economic which will meet the present demand without compromising for future generations with a global perception (UN 1987). LCA is considered to be part of a sustainable development strategy through quantifying values in a product or services life cycle. ELCA evaluates the environmental impacts and resources used throughout a product's life cycle which includes the procurement of raw materials to waste management (Finnveden et al. 2009). ELCA is used to measure the sustainability dimensions of a product (UNEP 2011).

Several studies have explored the sustainability issues of different waste management approaches across the globe (Al-Rumaihi et al. 2020). Zhou et al. (2018) provided lists of more than 30 life cycle assessment (LCA) studies conducted on different technologies of food waste management (composting, incineration, landfill, gasification, pyrolysis) between 2000 and 2015. According to Yadav and Samadder (2018), the LCA approach has been widely used to examine the environmental impacts of several sustainable waste management techniques. The most vital applications for LCA are the evaluation of the contribution of life cycle stages to overall environmental load, generally to improve product or to create process improvements for sustainable use of products systems (Muralikrishna and Manickam, 2017).

A product system of waste-to-compost is a very useful technique as it can recycle the total collected organic waste, significantly reduces environmental impact and landfill area requirements, and enhances economic benefits (Zurbrugg et al. 2005). Based on the waste concern report the high percentage of organic waste, both food waste from domestic sources and other organics from non-domestic sources in DCC, there is a great potential in recycling this organic waste into organic fertilizer through aerobic composting or into biogas through anaerobic digestion—a decentralized model (Waste Concern 2014).

Composting is a waste treatment method which is considered a less environmentally impactful alternative to conventional landfilling and incineration techniques, as it reduces the waste by recycling a large portion of waste into compost and produces fewer GHG emissions (Pergola et al. 2020). Organic wastes dominate Dhaka's MSW with nearly 70% (Alam and Qiao, 2020). Studies show that the establishment of a compost plant and compost market can create additional economic opportunities from waste collection (Bangladesh Database 2014). Compost sale and distribution could be very useful both economically and socially in Dhaka where the unemployment rate is around 5% (World Bank 2019). 'Bangladesh waste database' a report by Waste Concern shows that if all generated waste was collected and if this all-organic waste was recycled into compost, Bangladesh could potentially create an additional 24,981 jobs, produce 911,816 tons of organic compost per year, reduce 2,279,541 tons of CO₂e per year, and reduce its landfill area requirement by 5,014,991 m³ every year. Hence, it will be useful and essential to explore sustainable waste management options for Dhaka city and compare the sustainability aspects of the decentralized composting facility with existing landfill techniques to identify configurations that align with sustainable development goals.

For developing countries, small-scale decentralized community-based composting plants can be considered as a suitable option for treating municipal solid waste. This composting facility can be designed to reduce transport costs, make use of low-cost technologies, with manual labor, and minimize problems and difficulties encountered with backyard composting. To this date, no study has been

conducted in Bangladesh on a decentralized waste-to-compost process using LCA analysis; though, LCA applications to infrastructure systems are plenty in the literature. Therefore, the objective of this study was to conduct environmental LCA (ELCA) of decentralized municipal solid waste management strategies in comparison with the conventional landfilling options using waste-to-compost approach.

Materials and Methods

Study location

Dhaka, the capital city of Bangladesh is one of the most densely populated cities in the world. The metropolitan city of Dhaka with an area of 131 km² has a population density of more than 40,000 per km² (JICA, 2005). According to the Bangladesh Bureau of Statistics, the population of Dhaka metropolitan was around 9.6 million in 2001 which was almost doubled in 2011 (14.5 million). The increasing trend of population growth projects that Dhaka will be the top-ranking megacity by the year 2035 with a population of around 25 million (Yasmin and Rahman 2017). Figure 1 shows the trend of population growth and waste generation rate in the urban areas of Bangladesh. The figure shows that the urban population along with the average annual growth are increasing rapidly in the recent past. At the same time, due to the expansion of economic activities in the urban areas, the percentage of urban population among the total population is also growing fast which is projected to be 40% in the year 2025. The trend of waste generation shows a similar type of rapid upsurge from 2005. The projection of total urban waste generation in 2025 is 47,064 tons/day which was 27,654 tons/day in 2017 (Alam and Qiao 2020).

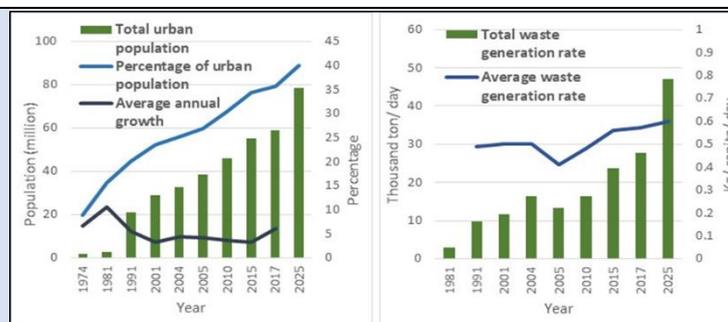


Figure 1: The trend of population growth and waste generation rate in the urban areas of Bangladesh (Source: Alam and Qiao 2020).

Waste collection plan

Disposal of MSW in Dhaka from the household to the primary or the final sites involves two steps of transportation of wastes, primary transportation

(from the generation site to STS) and from STS to the final treatment site. The primary transportation considers 3-wheeler rickshaw vans driven by informal waste collectors and employed by the local community

or outsourced by Municipality agency. A waste collectors van is a general manually driven vehicle. Its wheels and chassis are the same as the normal manually driven van or rickshaws (Figure. 2).



Figure 2: Waste collectors Van typically used for collecting waste from household door to door. (Source: Waste disposal & management in DCC, BUET, 2017).

At present, there are two major landfill sites for the whole city and a secondary transfer station at almost every ward. For the distance traveled for different scenarios, each ward was assumed to have an area of about 4 km². Based on the assumption of the area of a ward, the travel distance is approximately an average of 3 km from STS to the waste source. In the areas of primary collection, Primary Waste Collection Service Provider (PWCS), an NGO coordinates waste collections from households to STS. In 2016-2017, 340 private operators were registered with the PWCS. There are also unregistered operators collecting wastes from households to STS (BUET 2017). The secondary transportation involved the use of a 12-tonne container truck to travel about 17 km (on average for the wards) to reach the final dumping site at the two landfill sites.

Goal and scope

ELCA has been conducted to quantify the environmental impact categories for four scenarios of municipal solid waste including Scenario 1: Windrow composting (S1), Scenario 2: automated composting with EP-1000 composting machine (S2), Scenario 3: sanitary landfilling (S3), and Scenario 4: unsanitary landfilling (S4).

System boundaries

The “cradle-to-gate” approach was followed where the waste production at households was considered “the cradle”, and the compost as a final marketable product to be directed to “the gate”. In example, the final product (compost) for scenario S1 and S2 that could be sold, was sent to either the market, whereas in scenarios 3 and 4, the final product (waste) will end up at the landfill (Figure 3). Considering these assumptions, hypothetical systems were developed for

four scenarios to be compared for the household to decentralized waste to compost facility using windrow composting (S1), household to a decentralized location using an automated waste to compost EP-1000 machine (S2), household to sanitary landfill process (S3), and household to unsanitary/open dumping landfill process (S4). The system boundaries separately considered the four scenarios including S1, S2, S3, and S4 as main phases. The production system inputs comprised municipal solid waste (MSW), water, fossil fuel, and infrastructure at the secondary transfer station (STS), decentralized composting facilities, and landfills (Fig.3). The final compost production/bagging and/or landfilling (enclosed and open dumping) of waste consisted emissions to air, water, and land.

Main and sub-phases

Waste management process was the main phase of ELCA analysis. The sub-phases included waste generation at households and the four scenarios of waste processing including S1, S2, S3, and S4. The sub-phases considered processes of waste collection from households, storage, and segregation at secondary transfer stations for decentralized composting, and dumping (enclosed or open) in sanitary and unsanitary landfills. For input variables, Dhaka city was divided into 10 administrative zones with around 5 wards per zone. The average population per ward is roughly 120,000 persons.

Data generation and collection

The first phase of this study included data collection. Data regarding inputs (MSW produced at a household) and other materials and energy supply (including fuel, electricity, and water) were collected as part of background data. Emissions to air, water,

and land during these processes were also considered a part of background data under the guidelines of as per ISO 14040-14044 standard series (ISO 2006a, 2006b). The foreground data included information collected from waste management operations of the four scenarios (Figure 3b). The transport processes involved in various phases and sub-phases of this analysis were sourced from Ecoinvent v.371 (Moreno Ruiz et al. 2020) and the professional database

including Ecoinvent v.301 LCIA methods (Coulomb et al. 2015; Mutel et al. 2019). The main and sub-processes shown in the foreground and background data collection involved i) energy use (electricity in S1, S3, and S4 and solar power in S2), ii) diesel/fossil fuel consumption, iii) compost production (in S1 and S2), iv) food waste transport (MSW produced at households), and v) water consumption.

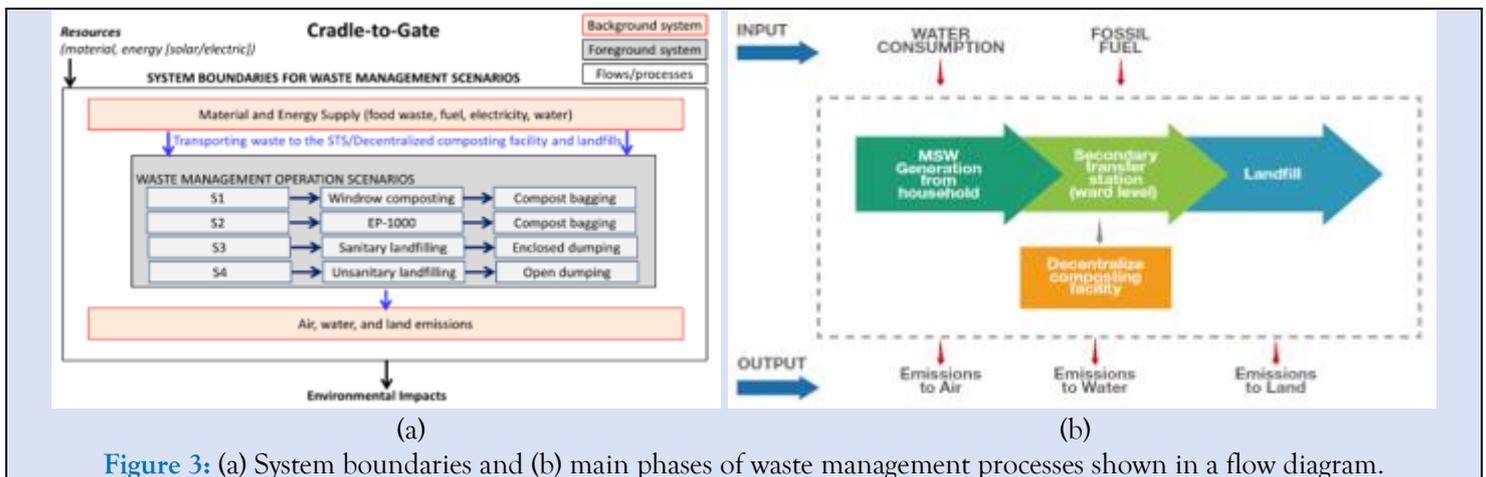


Figure 3: (a) System boundaries and (b) main phases of waste management processes shown in a flow diagram.

Two basic Ecoinvent processes are relevant for the one existing and three hypothetical scenarios based on landfilling and composting. For example, S1 and S2 consider two hypothetical community-based decentralized locations focusing on compost production using windrow and an automated EP-1000 waste to compost machine, respectively. The S3 and S4 scenarios attempt to replicate the existing MSW management unsanitary landfilling (with an option of open dumping) and a hypothetically centralized sanitary landfilling (enclosed dumping) for administrative zones (20 wards).

An additional assessment of global GHG emissions from cycling three-wheeler van was considered in this study. GHG emissions required to power a kilometer of walking and cycling for Bangladesh-based waste collector was estimated from secondary literature. Informal waste collectors who collect waste from household to the secondary transfer station usually uses three-wheeler rickshaw van. These vans are completely driven by physical labor without any automated machine or fossil-fuel-based energy; therefore, an attempt was made along with OpenLCA simulation to assess the environmental impact during this process. The values were calculated as a global average using estimates of energy availability and

dietary greenhouse gas emissions from a single global study (Mizdrak 2020). The additional energy intake that would be required for traveling by cycling using a three-wheeler rickshaw van relative to average daily activity was calculated by the GHG emissions associated with compensating for the additional energy expenditure. These estimates of the emissions per calorie are associated with current dietary patterns. The last step of this process was to explore the GHG emissions and body mass index impacts associated with partial compensation of energy expenditure (Mizdrak 2020). Based on the metabolic equivalent of task values estimated excess energy expenditure for Bangladesh was taken from Tilman and Clark (2014).

Assigned burdens

A predefined functional unit for this analysis was assigned as 1 megagram (Mg) (equivalent to 1 ton) of MSW. Emissions to air, water, and soil resources as well as energy consumptions have been calculated and are expressed per functional unit. Bartzas et al. (2015) are of view that every LCA analysis needs a balance between the burdens assigned for each phase and sub-phase and the environmental benefits. Therefore, normalization minimized the scale difference between

input data for food waste processing and the resultant outputs of compost bags or enclosed/open dumping, as adapted from Ecoinvent v.371. Normalizations were characterized based on the processing/product systems to characterize the total emissions within political/geographical boundaries such as global and/or specifically the United States or European Union. LCA results when normalized justify quantitative emissions from a marginal functional unit of a processed product for the selected environmental assigned burdens of a reference system (Norris 2001).

Impact categories

This ELCA considered four environmental impact categories namely global warming potential (GWP, kg of CO₂-eq Mg⁻¹ of waste), Fresh water aquatic ecotoxicity potential (FAETP, kg 1,4-DB-eq Mg⁻¹ of waste), Human toxicity potential (HTP, kg 1,4-DB-eq Mg⁻¹ of waste), and Terrestrial ecotoxicity (TEP, kg 1,4-DB-eq Mg⁻¹ of waste) using freely available database (i.e., LCIA v.202) and Ecoinvent v.301 LCIA methods as well as standards and definitions of the CML-IA Baseline (Guinée et al. 2001) that consider the ISO classification and characterization for these impact categories. These impact categories were selected based on Dhaka's environmental factors such as water bodies, lakes, and rivers which are adjacent to the landfill. Methane emission data were also extracted through Open LCA simulation for two landfills and two different types of decentralized composting.

Life cycle inventory

The inventory data were collected from various sources which include municipal corporation, the ministry of Environment and other literature reviews.

The inventory data generated from the four study scenarios, collected from the grey and scientific literature, and from the LCI databases (Ecoinvent v.371) were used for inputs. Some of the data generated from the literature is given in Table 1. Waste generation was calculated based on the available information. For example, considering a waste generation rate of 0.5 kg/capita/day the total waste generation would be 1200 tons/day for around 2.4 million population within four zones in DCC focusing on wards in Uttara. During LCA analysis, the outputs were normalized as the output flows required the use of functional units and boundaries (political/geographical) for each study scenario (Norris 2001; Hayashi 2013). Figure 3a illustrates scenarios S1 and S2 to focus on the community-based decentralization effect where composting facility at each ward was considered. Primary transportation is only by 3-wheeler van (Bangladesh database 2014). No secondary transportation by a fuel-using vehicle is necessary in the decentralized cases. For S1, hauling 1 Mg (1 ton) of waste for windrow composting would need moistening water (400 L of tap water), 50-kilowatt hour (kWh) of low voltage electricity to run the composting facility, and 5 L of diesel lubricant (Waste concern, 2014). Simulation was conducted based on 1 Mg of kitchen waste which generates 0.25 Mg of compost. However, S2 utilizes an automated waste-to-compost machine (EP-1000) which is operated by solar panels. This automated machine was situated in a decentralized location with the composting facility where all electricity need, i.e., lights, fans, small scale machines etc. are also run by energy generated from PV (photovoltaic) cells. The relevant data are shown below:

Table 1: Consumption of fuel for major equipment/machineries in landfill and Decentralized Waste to Compost Facility.

Resource/tools	S1: Windrow based	S2: EP-1000 based	S3: Sanitary landfilling	S4: Unsanitary landfilling
Excavator (Diesel)	N/A	N/A	18.9 L per hour	18.9 L per hour or less
Dump truck (Diesel)	NA (Waste was carried by 3-wheeler rickshaw vans operated manually)	N/A	Same as an unsanitary landfill	Get around 11084 L per hour for short hauls, and 23.4 L for highway hauling.
Bulldozer (Diesel)	N/A	N/A	~ 15 L	between 13.3 L and 24.7 L.

Composting machine	N/A	Solar-powered EP-1000 automated waste-to-compost machine	N/A	N/A
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The inventory results for four scenarios are shown in Table 2, which summarizes the emissions to the atmosphere due to the management of wastes considering the consumption of 1.0 L of diesel for transport and 0.2 L of diesel for management of 1000 kg of waste at the respective facilities (based on primary data collection). The energy calculation was made based on consumption of 18.9 L per hour or less by an excavator, 11084 L of diesel per hour for short hauls, 23.4 L of diesel for highway hauling by a dump truck, and between 13.3 L and 24.7 L of diesel by a bulldozer. The limitations include that although

these are direct emissions of pollutants associated with composting and landfilling, these are not real emission data, and that the emissions based on generic Ecoinvent datasets might not fit with the situation in Bangladesh. It was assumed that the normalization function of OpenLCA for Ecoinvent datasets is accepted for most of the countries to address such situations; i.e., the difference in political boundaries such as European Union, USA, or globe is addressed when data provider in OpenLCA is linked to Consequential, S - GLO.

Table 2: The output data (pollutants determined in kg) from treating of the functional unit of 1 Mg of municipal solid waste (food waste) transported to the respective facility at the energy hauling cost of 1.73×10^3 MJ/km sourced from diesel consumption.

Composting	kg/Mg	Landfilling	kg/Mg
Methane	0.4	Carbon dioxide	69.8
Ammonia	0.14	Copper	0.06
Nitrogen dioxide	0.12	Lead	0.041
Nitrogen oxides	0.0023	Nickel	0.148
Carbon monoxide	0.0004	Methane	31.1
Sulfur oxides	0.0019	Methane, hydrochlorofluorocarbon	0.337
Cadmium	0.012	Nitrogen	4.256
		Nitrogen oxides	0.0588
		Phosphorus	6.72
		Particulate matter	2.17
		Volatile organic compound	2.89
		Zinc	0.34
		Sulfur dioxide	5
		Wastewater	0.1 m ³

Greenhouse Gas Emissions from Pedal Rickshaw Waste Collection

Greenhouse gas emissions from additional food consumption are estimated for rickshaw drivers involved in waste collection, to enable a comparison with GHG emissions from mechanized waste collection. A total number of trips per day for these rickshaw vans (each weighing 640 kg in addition to the load of waste and the weight of driver) are taken and added together to calculate the total GHG

emissions from the primary collection route which is household to secondary transfer station once daily. This emission is then added to the total GHG emission from each process since all primary transportations were considered as rickshaw vans in this model. For ten administrative zones, there are approximately 340 vans. Table 3 shows estimates of energy availability and dietary greenhouse gas emissions for Bangladesh.

Table 3: Estimates of energy availability and dietary greenhouse gas emissions for Bangladesh calculated by Tilman and Clark (2014) and Mizdrak (2020)

Description	Dietary greenhouse gas emissions* (kgCO ₂ -eq /capita/day)	Emissions per 100 kcal (kgCO ₂ -eq /100kcal)	Estimated excess energy expenditure (kcal/km)
For hauling waste to a distance of 1 km (from literature)	2.71	0.101	29

*Emissions include CO₂, N₂O, and CH₄

An assumption was made for total calorie burned by the waste collector based on the total weight of the waste collector and the waste. An estimated total

weight of 800 kg is considered for each van with waste and the waste collector. Based on the calories burned for cycling / biking formula which is

$$\text{Calories burned per minute} = (\text{MET} \times \text{body weight in Kg} \times 3.5) \div 200 \quad (\text{equation -1})$$

where MET (metabolic equivalent of task) is a measurement of the energy cost of physical activity for a period of time. MET values are taken from (Britannica 2023). The assumption was made based on competitive bicycling activities with heavy load. The MET value for this calculation taken was 16 calories/minute-kg. Therefore, the calories burned for a waste collector for a total hour of activity to work around 1 ton of waste is calculated from equation 1 which is approximately $((16 \times 65 \text{ kg} \times 3.5)/200) \times 60 = 1092$ calories. Based on this result, emissions per 100 kcal (kgCO₂-eq/100kcal) was considered to find out the total GHG emission from all 340 vans operating from household to STS, using literature given in Table 1. The total amount GHG calculated was $1.092 \text{ kcal} \times 0.101 \text{ Kg CO}_2 / \text{kcal} = 0.103 \text{ Kg CO}_2 \text{ eq}$ for each pedal van 1 km. The total GHG emission estimated for all 340 vans were added to the total GHG emission from OpenLCA simulation at the end with each process.

Life cycle impact assessment

The life cycle assessment conducted for this study considered four scenarios of municipal organic waste management. The first two scenarios (S1 and S2) were the proposed windrow composting and automated composting with the EP-1000 machine, respectively. Their environmental impact categories namely global warming potential (GWP100), freshwater aquatic ecotoxicity potential (FAETP), human toxicity potential (HTP), and terrestrial ecotoxicity potential (TEP) were compared with the two conventional in-practice scenarios including sanitary (S1) and unsanitary (S4) landfilling.

ELCA studies use environmental impact categories to gauge the impacts of waste management on the ecosystem and human health. For example, GWP100

is a system to measure the global warming potential of GHGs based on a CO₂ score of 1 equivalent to a CH₄ score of 28 meaning that over a period of one year, CH₄ is 28 times more potent than 1 kg of CO₂. The impacts of GWP100 are classified in terms of CO₂ equivalent (CO₂eq) (Itoiz et al. 2013). Chemicals can be released into the environment at any point in a product's life cycle. Hundreds of chemicals may be included in the emission inventory of various goods, and many of these compounds have the potential to have ecotoxic effects on aquatic and terrestrial ecosystems, resulting in harm to the quality of these ecosystems. The category FAETP is used to measure such impact of waste management. Similarly, for HTP, human health is considered prone to and is affected by the emissions of some substances such as heavy metals. The toxicity of the environment caused by such emissions is assessed by a tolerable concentration of substances in water and air. The tolerable concentration of various substances is usually given air quality guidelines in terms of tolerable daily intake and acceptable daily intake HTP, expressed in the unit, kg 1,4-dichlorobenzene equivalent (1,4-DB eq.). Emissions from municipal solid waste produce a variety of hazardous compounds that could multiply several times on-site and negatively affect freshwater and terrestrial ecosystems gauged by FAETP and TETP (also expressed in the unit, 1,4-DB eq.). Municipal waste that has been improperly managed therefore has the potential to be terrestrially ecotoxic and to degrade the environment. The ELCA analysis used data collected during two study phases; Phase that comprised collecting primary and secondary data on current landfilling and proposed decentralized composting processes. Phase II included conducting a comparative LCA of these waste treatment options using simulation software

(OpenLCA) with Ecoinvent v.371 (Moreno Ruiz et al. 2020) database. In OpenLCA, the comparative assessments were conducted using the standardized procedural framework of the International Organization for Standardization (ISO) 14040 (ISO 2006a) and 14044 (ISO 2006b) under guidelines of UNEP (UN Environment Programme) for ELCA that consists of four phases; i) goal and scope, ii) inventory, iii) impact assessment, and iv) interpretation.

Interpretation of Results

Global warming potential

This section interprets the results of the LCI and/or the LCIA. A summary of the ELCA results is presented in Table 4. The total GWP100 for composting from S1 (windrow-based) and S2 (EP-1000-based) scenarios resulted in the respective emissions of 1.14 million kg of CO₂-eq Mg⁻¹ and 412 kg of CO₂-eq Mg⁻¹ of waste processed. These

emissions are considerably lower as compared to emissions noticed from S3 (sanitary landfilling) and S4 (unsanitary landfilling), which were respectively about 2.1 million kg of CO₂-eq Mg⁻¹ of waste and 3.9 million kg of CO₂-eq Mg⁻¹ of waste. This is mainly due to the lower volume of organic waste in landfills which is a potential source for CH₄ generation. These findings concur with the report of Maria et al. (2020) who is of view that emissions of GHGs from waste collection and landfills have a significant contribution to the degradation of the environment and that direct landfill emissions are the major contributors to GHG inventory. About 11% of the global CH₄ emissions come from landfills as they are the largest anthropogenic source of CH₄ emissions after agricultural and enteric fermentation; the emissions from landfills are expected to grow more and more (USEPA 2006).

Table 4: Overall result for comparison of impact assessment calculated from environmental life cycle assessment analysis while considering the functional unit 1 Mg of municipal food waste managed/treated under the four study scenarios (S1-S4). The units for impact categories are given in footnote of the table.

Impact category	S1: Windrow based	S2: EP-1000 based	S3: Sanitary landfilling	S4: Unsanitary landfilling
GWP100	1143615	412	2123677	3874117
FAETP	1865	0.525	6570043	6619467
HTP	108866	38.2	657228	617623
TEP	511	0.18	4805	4649

GWP100: global warming potential (kg of CO₂-eq Mg⁻¹ of waste), FAETP: freshwater aquatic toxicity potential (kg 1,4-DB-eq Mg⁻¹ of waste), and HTP: human toxicity potential (kg 1,4-DB-eq Mg⁻¹ of waste), and TEP: terrestrial ecotoxicity potential (kg 1,4-DB-eq Mg⁻¹ of waste).

Landfill is one of the common waste management methods used in many developing countries (Bangladesh database 2014). It is also the existing final disposal technique practiced by the municipal authority of Dhaka (JICA 2005; Alam and Qiao 2020). Landfill has several negative impacts such as water and air pollution, transmission of diseases, encroachment of wetlands, water logging and flash flooding, aesthetic nuisance, and economic losses (Parvin and Begum 2018). Also, the decomposition of organic waste under anaerobic conditions produces methane, a potent GHG, making landfill a major contributor to climate change. Landfill has another drawback as it demands greater land area with the increasing waste generation.

Freshwater aquatic toxicity potential

The reason behind selecting the impact categories of this ELCA analysis was the prevailing factors most likely to impact the environment of the study area. For example, waste management facilities such as STS

or landfills in Dhaka being in the vicinity of water bodies, lakes, and rivers could result in aquatic, human, and terrestrial toxicities. Results presented in Table 4 show that the FAETP category for composting from S1 and S2 scenarios resulted in the emission of 1865 kg 1,4-DB-eq Mg⁻¹ of waste and a negligible emission of only 0.525 kg 1,4-DB-eq Mg⁻¹ of waste processed. Similar to GWP100, these emissions are considerably lower as compared to emissions resulted from S3 (6.57x 10⁵ kg 1,4-DB-eq Mg⁻¹ of waste) and S4 (6.17x 10⁵ kg 1,4-DB-eq Mg⁻¹ of waste). The reason for fewer emissions from S1 and S2 scenarios was the production of composting as compared to enclosed dumping in the case of S3 and open dumping of MSW in the case of S4.

Human toxicity potential

Since during the windrow composting waste products are placed along long but narrow strips piled wastes that are regularly agitated and/or turned upside down to mix the waste materials under passive aeration,

HTP resulting from S1 (1.1×10^5 kg 1,4-DB-eq Mg^{-1} of waste) was greater than from S2 (-38.2 kg 1,4-DB-eq Mg^{-1} of waste). The latter uses machines for composting the waste materials under an environmentally friendly operation. The EP-1000 machine as part of S2 and its whole facility is operated by solar power. About windrow composting, it is essential to note that there are some negative aspects of the composting process as well (Pergola et al. 2020). Principally, it is related to the byproduct of the compost reaction. There are different techniques of composting with two major types: aerobic and anaerobic. The common emission from these techniques is CO_2 emission from decomposing organic matter in the compost pile (Pergola et al. 2020). However, these are not usually acknowledged as additional greenhouse gas emissions as they are biogenic and part of the short-term carbon cycle (Brown et al., 2008). The anaerobic approach includes methanogenic and denitrification processes during composting which lead to emissions of CH_4 , nitrous oxide, and ammonia (Brown and Subler 2007, Amlinger et al. 2008; Boldrin et al. 2009).

However, HTP values of S3 (0.66 million kg 1,4-DB-eq Mg^{-1} of waste) and S4 (0.62 million kg 1,4-DB-eq Mg^{-1} of waste) were about 6 times more than that of S1 (Table 4). With the present plan of DCC, the sanitary and unsanitary landfills are not fully operational resulting in a minor difference within the HTP values of the two landfills (S3 vs. S4). These are additional greenhouse gas emission and also leads to odor problem. CH_4 and nitrous oxide both are more dangerous greenhouse gases than CO_2 as they are more efficient than CO_2 at holding heat (Brown and Subler, 2007). Environmental LCA conducted on different composting techniques and using different types of wastes as raw material for compost also indicated the direct and indirect emissions from the composting process (Pergola et al. 2020).

Global waste management techniques have improved manifolds with lesser environmental impact over the last few decades (Mehta and Sirari, 2018). Sanitary landfills, incineration with waste to energy, anaerobic digestion to biogas, and waste to compost are some of the major techniques. Based on several LCA studies composting showed lesser environmental impacts than the other techniques (Malmir et al. 2020). Advanced pyrolysis, and gasification showed more benefits in terms of energy recovery (Eren et al. 2019). However, landfill is the most common practice in

developing countries as a means of waste management and they are more prone to impacted by HTP. Informal waste recycling is a common livelihood for the urban poor in low- and middle-income countries including Bangladesh. About 1 percent of the urban population, or more than 15 million people, earn their living informally in the waste sector (Medina 2010). In urban centers in China alone, about 3.3 million to 5.6 million people are involved in informal recycling (Linzner and Salhofer 2014). Waste pickers are often a vulnerable demographic and are typically women, children, the elderly, the unemployed, or migrants. They generally work in unhealthy conditions, lack social security or health insurance, are subject to fluctuations in the price of recyclable materials, lack educational and training opportunities, and face strong social stigma. Therefore, these waste collectors are more prone to HTP since they are exposed to the landfill and other means of waste management process.

Terrestrial ecotoxicity potential

The analysis showed that the scenario from decentralized composting using an automated waste to compost machine (i.e., S2) had a positive environmental impact with a TEP value of -0.18 kg 1,4-DB-eq Mg^{-1} of waste (Table 4). The second decentralized composting scenario; i.e., windrow composting (S1) had the second lowest potential damage to the terrestrial ecosystem with a TEP value of 511 kg 1,4-DB-eq Mg^{-1} of waste. These values were lower than the impact compared to that of the landfill scenarios of enclosed and open dumping in landfills; i.e., S3 (4805 kg 1,4-DB-eq Mg^{-1} of waste) and S4 (4649 kg 1,4-DB-eq Mg^{-1} of waste).

Overall contribution of inputs and outputs to impact categories

Overall, percent contributions to the impact categories GWP, HTP, FAETP, and TEP for MSW management/production systems' inputs and outputs for the four scenarios is shown in Figure 4. Specifically, for contributions of S1 (windrow composting) and S2 (composting EP-1000 machine) the compost production process had the highest contribution to all the four impact categories followed by transportation of food waste from households to STS (Figs. 4ab). The least contribution during S1 was the energy use as well as for S2 that used solar-powered EP-1000 composting machine (Figure 4b).

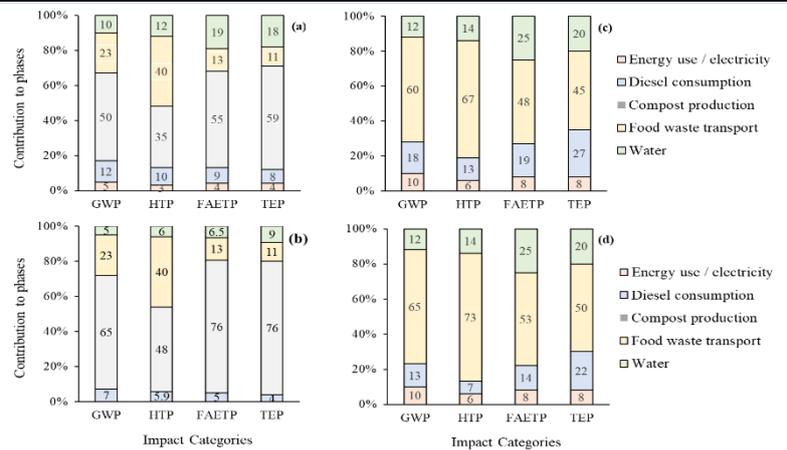


Figure 4: (a) Percent contribution of various production systems inputs and outputs to the impact categories (GWP: global warming potential; HTP: human toxicity potential; FAETP: freshwater aquatic ecotoxicity potential; TEP: terrestrial ecotoxicity potential for waste management (a) Scenario 1 of windrow composting, (b) Scenario 2 of EP-1000 machine composting, (c) Scenario 3 of sanitary landfilling, and (d) Scenario 4 of unsanitary landfilling.

During S3 (enclosed dumping) and S4 (open dumping) scenarios where the food waste was managed under sanitary and unsanitary conditions, zero contribution was resulted for compost production process and the maximum contributions were calculated for food waste transportation from household to the landfill sites that were located at a longer distance from households than the STS (Figs. 4cd). Therefore, the highest contributions to all impact categories during S3 and S4 were from food waste transport. The second and third highest contribution during S3 and S4 were from diesel consumption for the onsite machinery and water used, respectively.

ELCA aids in calculating the environmental burdens of a product system, process, or activity by identifying and quantifying the energy and materials used and wastes released into the environment. The assessment considers the entire life cycle of a product, process, or activity, including the final disposal as well (Consoli et al. 1993), making it an appropriate tool to adopt when comparing waste management practices. Concerned with the environmental impact of composting technologies, some studies have mainly focused on atmospheric emissions (Güereca et al. 2006; Iriarte et al. 2009), most of them performed at pilot or laboratory scale and only a few at real scale and just a few of them were studied using ELCA (Rives et al. 2010). The presented work considered ELCA and achieved comprehensive sets of results for waste management scenarios in DCC, Bangladesh.

Conclusion

Composting is a process of solid waste management that creates a recycled product from organic wastes that can be used as a replacement of peat, fertilizer, and manure in agricultural activities, which is carbon-rich and free of most pathogens and weed seeds (Pergola et al. 2020). This is considered a more sustainable alternative to conventional landfilling and incineration for waste management. The recycled product is good for agricultural soil in many ways such as, incorporating organic matter, nutrients, and electrolytes for soil, lowering the demand for fertilizers and pesticides, improving soil texture and structure, increasing capacity for carbon storage, etc. (Saer et al. 2013). Therefore, composting is getting greater attention globally for sustainable agriculture and soil management as well. The process of composting is an environmentally friendly solution for waste management, yet in terms of sustainability, there are various fields to consider. This is because, many studies reported negative environmental impacts such as emission of harmful gases, odor, etc. (Aziz et al. 2016). Considering sustainability, the economic and social factors of composting should also be assessed before application as these factors vary in different countries with respect to their culture.

Four waste management scenarios were compared. Sanitary and unsanitary landfills and two separate decentralized waste to compost facilities; one with windrow composting and the other one with EP-1000—an automated waste-to-compost machine. OpenL CA software was used to assess the ELCA. The impacts analyzed were based on the level of emissions from each process for four environmental impact categories of global warming, freshwater aquatic toxicity, human toxicity, and terrestrial ecotoxicity

potentials for landfills are much higher than decentralized composting facility. During the comparison, it was found that the emissions for the four selected were higher for enclosed or open dumping scenarios of municipal solid waste management than for the two scenarios of producing compost from municipal waste. The calculated FAETP and HTP results revealed that landfill has a higher impact than composting. If the waste generated by DCC were used to produce compost using a decentralized composting facility within the city, the outcome would be a substantially reduced emissions profile throughout the life cycle when compared to using the waste taken to landfill. The results of this study show a great possibility of greater damage to the environment when an unsanitary landfill is used and a domino effect would cause not only Dhaka but the world a major environmental crisis if not given a proper sustainable solution. As discussed, the development of decentralized waste to compost facilities in Dhaka as well as other cities can provide solution to better waste management and can have greater potential to have positive environmental effect. Future research should focus on the efficacy of the decentralized composting facility with more indicators to facilitate implementation strategy for policymakers.

Declarations

Ethical Approval

Not applicable.

Consent to Participate

Not applicable.

Consent to Publish

Not applicable.

Author Contributions

All authors contributed to the study's conception and design. Material preparation, data collection, and analysis were performed by Azad Ibn Ashraf, Eugene Mohareb, and Maria Vahdati. The first draft of the manuscript was written by Azad Ibn Ashraf. Farhat Abbas edited the paper. Eugene Mohareb and Maria Vahdati commented on the first version that was improved to its final form by Azad Ibn Ashraf and Farhat Abbas. All authors read and approved the final manuscript.

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Competing Interests

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Availability of data and materials

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