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 expanding rapidly in parallel with population expansion and urbanization, posing municipal solid waste management difficulties. This study examined the environmental impacts of domestic organic waste generated in the Dhaka North City Corporation in Bangladesh, a country with a fast-growing population and economy. No previous environmental life cycle assessment has been conducted in a decentralized waste-to-compost facility in Dhaka, nor has the environmental impact of manual informal labor be considered. Four major waste management scenarios were compared: conventional windrow composting (S1), proposed automated composting using an EP-1000 machine (S2), and existing practices of sanitary (S3) and unsanitary (S4) landfilling. The four scenarios' environmental impacts were assessed using OpenLCA software. Environmental Life cycle assessment (ELCA) of the four scenarios was conducted using OpenLCA software for their environmental impact. Results revealed that 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 CO_2-eq Mg^{-1}) and S2 (411 kg CO_2-eq Mg^{-1}) were multifold lower than emissions from conventional landfilling of S3 (~ 2.12 million Mg of CO_2-eq Mg^{-1}) and S4 (~ 3.87 million Mg of CO_2-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. 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 · Informal labor · Composting · Sustainable solid waste management

1 Introduction

Management of municipal solid waste (MSW) is an emerging challenge exhibited in developing countries, facing accelerated urban population growth, unplanned urbanization, and industrialization [1]. 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 Mg in 2016 to 3.40 billion Mg in 2050 [2]. Release

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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 [3]. In 2016, an estimated 1.6 billion Mg of carbon dioxide equivalent (CO_2-eq) GHG emissions directly resulted from MSW, representing approximately 3.2% of global emissions [4]. These emerging environmental problems bring out the importance of the MSW management challenges [5].

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 [6] and currently ranks the world's eleventh largest megacity with a population of 25 million living in an area of 1528 km^2. 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 [7]. 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 Mg to 1.20 million Mg yearly. This suggests that from 2015 to 2020, Dhaka City Corporation (DCC) might have managed over 5.6 million Mg of waste, dominantly organic contents [8]. MSW in Dhaka is characterized by a high organic matter fraction in the range of 60–80% on a wet basis [1, 7]. DCC is the main responsible authority to manage Dhaka's MSW within a service area of around 360 km^2 [9]. Waste generated, initially stored at the households, is primarily transported to the secondary storage locations such as dustbins, containers, and secondary storage points called secondary transfer stations (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 [9]. There are currently two major landfill sites for Dhaka's MSW and no site has the complete sanitary facilities, although there are plans to provide such facilities shortly [10]. Few studies have examined the MSW context in Dhaka around lessening the environmental burden of waste to landfills [10]. Waste management in populous cities such as Dhaka presents numerous challenges due to the large volumes of MSW generated, limited landfill space, and the environmental impacts associated with conventional waste disposal methods like incineration and landfilling. Unsanitary landfills contribute to air, water, and soil pollution, while the incineration of waste emits harmful greenhouse gases and toxins. Composting offers a sustainable alternative by diverting MSW and transforming it into nutrient-rich soil. This process reduces methane emissions, improves soil health, and can help mitigate the urban heat island effect. In Dhaka, where space is often limited and waste management infrastructure is under strain, composting can significantly reduce waste volume, lower disposal costs, and contribute to a circular economy by closing the loop between organic waste generation and agricultural needs. By promoting composting on both an individual and municipal scale, Dhaka can address waste management challenges while advancing environmental sustainability and supporting urban resilience.

Authors in [11] have focused on community-level engagement in MSW. Reference [12] 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 [13]. Around 40–60% of waste remain uncollected due to the absence of awareness, motivation, expertise, and budget [14]. 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 [15].

According to the World bank report [16], 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 [17]. 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 [18]. ELCA is used to measure the sustainability dimensions of a product [19].

Several studies have explored the sustainability issues of different waste management approaches across the globe [20]. Researchers in [21] 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 the findings in [22], 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 [23].

A product system of waste-to-compost is a very useful technique as it can recycles the total collected organic waste, significantly reduces environmental impact and landfill area requirements, and enhances economic benefits [24]. 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 [25].

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 [26]. Organic wastes dominate Dhaka's MSW with nearly 70% [7]. Studies show that the establishment of a compost plant and compost market can create additional economic opportunities from waste collection [10]. Compost sale and distribution could be very useful both economically and socially in Dhaka where the unemployment rate is around 5% [6]. The '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 Mg of organic compost per year, reduce 2,279,541 Mg of CO_2eq per year, and reduce its landfill area requirement by 5,014,991 m^3 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. The Waste Concern study reveals the impact of landfills on environmental burdens facing society. In addition, it also highlights the potential danger of total greenhouse gases from a landfill. The Waste Concern 2014 report also evaluates the economic benefit of a decentralized composting facility as a pilot study. However, there was no study on environmental, social, or economic life cycle assessment on the decentralized waste-to-compost facility. Several Soul American countries including Peru and Brazil studied the social impact of various informal waste collectors, however, they did not conduct any comprehensive study on the social life cycle assessment between formal and informal waste collectors in a decentralized waste-to-compost facility. To date, no study has been conducted in Bangladesh on a decentralized waste-to-compost process using LCA analysis; further, examining the environmental impacts of manual labor in comparison to mechanized alternatives is under-studied as these impacts are not necessarily negligible. Therefore, the objective of this study was to conduct an environmental LCA (ELCA) of decentralized municipal solid waste management strategies in comparison with the conventional landfilling options using a waste-to-compost approach. Further novelty of this study comes from the consideration of emissions from informal manual labor as opposed to mechanized waste collection.

2 Materials and methods

2.1 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 km^2 has a population density of more than 40,000 per km^2 [9]. 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 [13]. 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 Mg/day which was 27,654 Mg/day in 2017 [7].

2.1.1 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

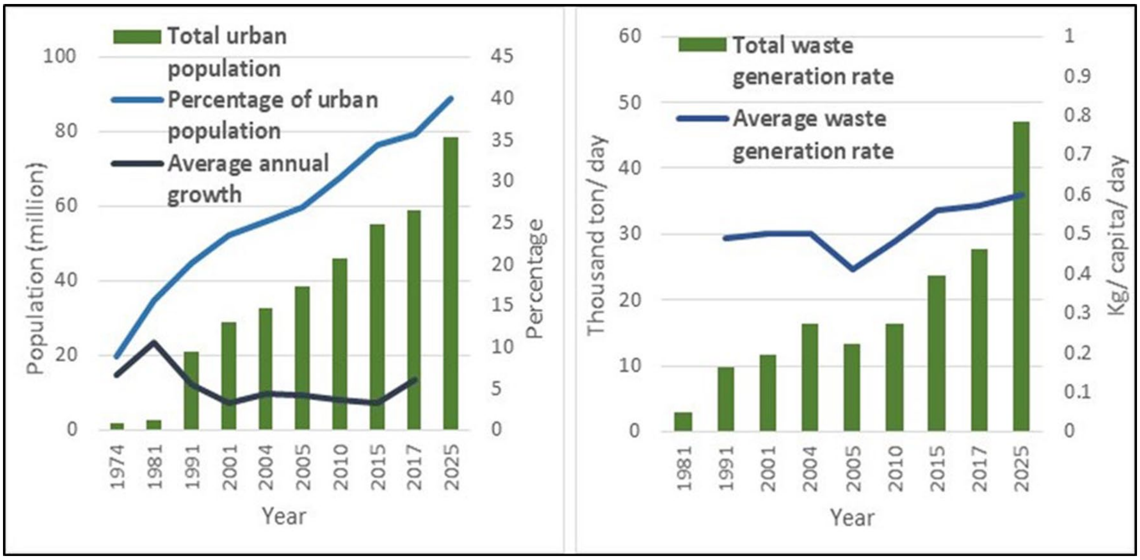

Fig. 1 The trend of population growth and waste generation rate in the urban areas of Bangladesh. *Source:* [7]

transportation considers 3-wheeler rickshaw vans driven by informal waste collectors and employed by the local community or outsourced by a Municipality agency. A waste collectors van is a generally manually driven vehicle. Its wheels and chassis are the same as the normal manually driven van or rickshaws.

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 km^2. 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 (PWCSP), an NGO coordinates waste collections from households to STS. In 2016–2017, 340 private operators were registered with the PWCSP. There are also unregistered operators collecting wastes from households to STS [27]. The secondary transportation involved the use of a 12-Mg container truck to travel about 17 km (on average for the wards) to reach the final dumping site at the two landfill sites.

2.2 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).

2.2.1 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 (Fig. 2). 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 compositing facilities, and landfills (Fig. 2). The final compost production/bagging and/or landfilling (enclosed and open dumping) of waste consisted emissions to air, water, and land.

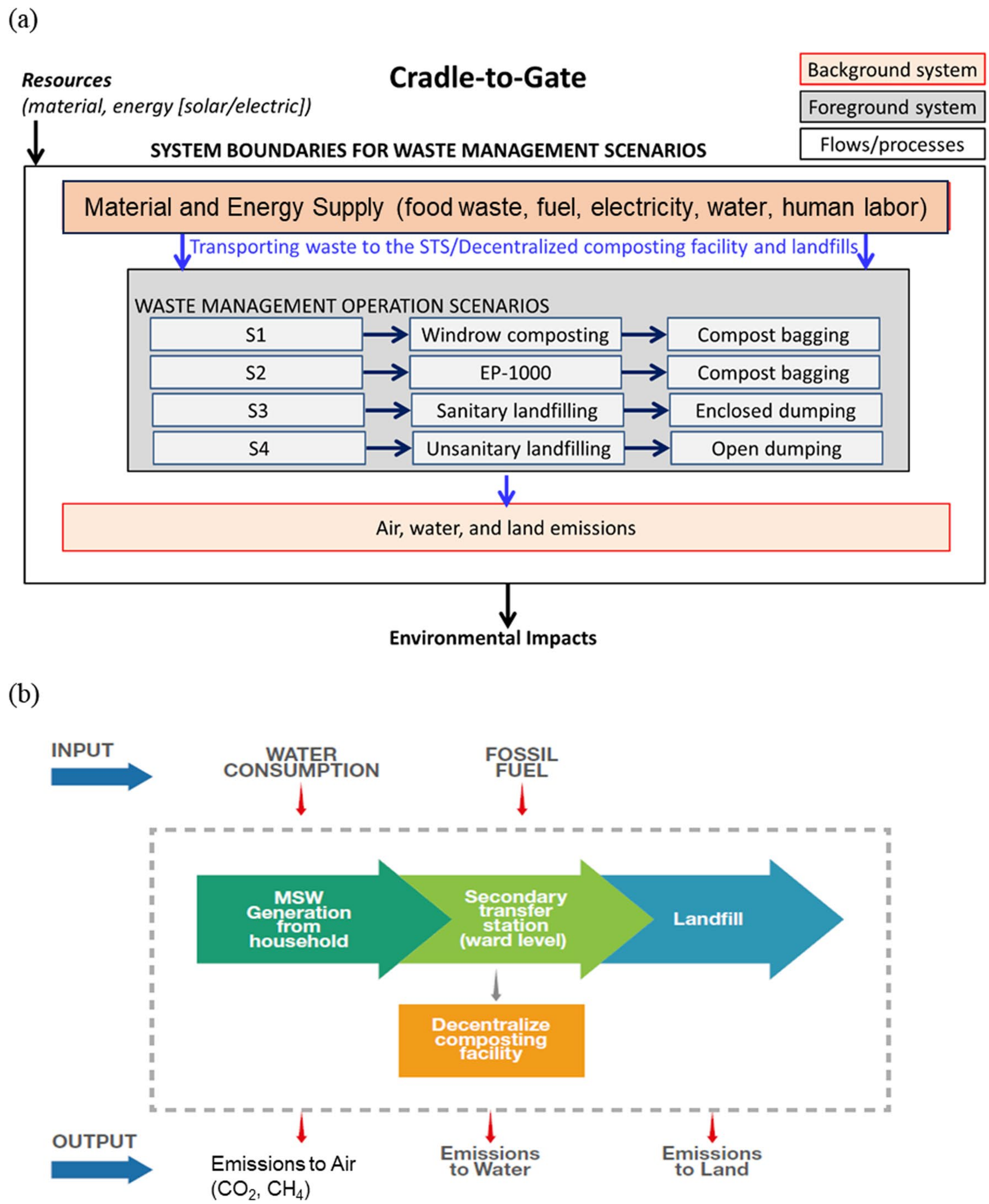

Fig. 2 **a** System boundaries and **b** main phases of waste management processes shown in a flow diagram

2.2.2 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.

2.2.3 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 [28]. The foreground data included information collected from waste management operations of the four scenarios (Fig. 2b). The transport processes involved in various phases and sub-phases of this analysis were sourced from Eco Invent v.371 [29] and the professional database including Eco Invent v.301 LCIA methods [30], 31. 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.

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 hypothetically centralized sanitary landfilling (enclosed dumping) for administrative zones (20 wards).

An additional assessment of global GHG emissions from cycling three-wheeler vans was considered in this study. GHG emissions required to power a kilometer of walking and cycling for Bangladesh-based waste collectors were estimated from secondary literature. Informal waste collectors who collect waste from households to the secondary transfer station usually use three-wheeler rickshaw vans. 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 [32]. 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 [32]. Based on the metabolic equivalent of task values estimated excess energy expenditure for Bangladesh was taken from [33].

2.2.4 Assigned burdens

A predefined functional unit for this analysis was assigned as 1 megagram (Mg) (equivalent to 1 Mg) 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. [34] are of the 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 [35].

2.2.5 Impact categories

This ELCA considered four environmental impact categories namely global warming potential (GWP, kg of CO_2-eq Mg^{-1} of waste), Freshwater 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 Eco invent v.301 LCIA methods as well as standards and definitions of the CML-IA Baseline [36] 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 adjacent to the landfill. Methane emission data were also extracted through Open LCA simulation for two landfills and two different types of decentralized composting. Other environmental burdens such as impact on land use, eutrophication, and ozone layer depletion were considered as similar environmental impact categories with the GWP mentioned above, HTP, FAETP, and TEP. Monte Carlo analysis was conducted in OpenLCA simulation, using several iterations, to compare the four scenarios of waste management by calculating their statistical indicators such as standard deviation.

2.3 Life cycle inventory

The inventory data were collected from various sources which include municipal corporations, 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 (Eco invent 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 Mg/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 [35, 37]. Figure 2a 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 [10]. No secondary transportation by a fuel-using vehicle is necessary in decentralized cases. For S1, hauling 1 Mg of waste for windrow composting would need moistening water (400 L of tap water), 50 kilowatt hours (kWh) of low-voltage electricity to run the composting facility, and 5 L of diesel lubricant [8]. 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 needs, i.e., lights, fans, small-scale machines, etc. are also run by energy generated from PV (photovoltaic) cells. The relevant data are shown below:

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, 11,084 L of diesel per hour for short hauls, 23.4 L of diesel for highway hauling by a dump truck, and between 13.3 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 the emissions based on generic Eco invent datasets might not fit with the situation in Bangladesh. It was assumed that the normalization function of OpenLCA for Eco invent 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.

2.3.1 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. The 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 the 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 were approximately 340 vans. The estimates of energy availability and dietary greenhouse gas emissions for Bangladesh comprised hauling MSW to a distance of 1 km resulting in 2.71 kgCO_2-eq/capita/day for dietary greenhouse gas emissions, 0.101 kgCO_2-eq/100 kcal as emissions per 100 kcal (*emissions include CO_2, N_2O, and CH_4*), and 29 kcal/km as estimated excess energy expenditure [32, 33].

An assumption was made for the total calories 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

Table 1 Consumption of fuel for major equipment/machinery 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 11,084 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

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

$$\text{Calories burned per minute} = (\text{MET} \times \text{body weight in kg} \times 3.5) \div 200 \tag{1}$$

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 [38]. The assumption was made based on competitive bicycling activities with heavy loads. The MET value for this calculation taken was 16 cal/min-kg. Therefore, the calories burned by a waste collector for a total hour of activity to work around 1 Mg of waste is calculated from Eq. (1) which is approximately $((16 \times 65 \text{ kg} \times 3.5)/200) \times 60 = 1092$ cal. Based on this result, emissions per 100 kcal (kgCO_2-eq/100 kcal) were considered to find out the total GHG emission from all 340 vans operating from household to STS, using the literature given in Table 1. The total amount of GHG calculated was 1.092 kcal $\times$ 0.101 kg CO_2/kcal = 0.103 kg CO_2 eq for each pedal van 1 km. The total GHG emission estimated for all 340 vans was added to the total GHG emission from the OpenLCA simulation at the end of each process.

2.4 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 CO_2 score of 1 equivalent to a CH_4 score of 28 meaning that over one year, CH_4 is 28 times more potent than 1 kg of CO_2. The impacts of GWP100 are classified in terms of CO_2 equivalent (CO_2eq) [39]. 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 the Eco invent v.371 [29] database. In OpenLCA, the comparative assessments were conducted using the standardized procedural framework of the International Organization for Standardization (ISO) 14040 and 14044 [28] under guidelines of UNEP (UN Environment Program) for ELCA that consists of four phases; i) goal and scope, ii) inventory, iii) impact assessment, and iv) interpretation.

2.5 Interpretation of results

2.5.1 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 3. 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 CO_2-eq Mg^{-1} and 412 kg of CO_2-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 CO_2-eq Mg^{-1} of waste and 3.9 million kg of CO_2-eq Mg^{-1} of waste. This is mainly due to the lower volume of organic waste in landfills which is a potential source for CH_4 generation. These findings concur with the report of [40] who is of the 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 CH_4 emissions come from landfills as they are the largest anthropogenic source of CH_4 emissions after agricultural and enteric fermentation; the emissions from landfills are expected to grow more and more [41].

Landfill is one of the common waste management methods used in many developing countries [10]. It is also the existing final disposal technique practiced by the municipal authority of Dhaka [7, 9]. 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 [42]. 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.

Regarding the use of manual labor compared with the mechanized collection of waste, the implications of these on total GHG emissions were found to be less relative to the total GHG emission from the mechanized collection. When comparing the two, mechanized collection demonstrates a higher contribution to overall carbon dioxide and methane generation than informal waste collectors. This demonstrates the relatively less contribution from dietary energy demand relative to fossil demand in this instance.

2.5.2 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

Table 3 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)

Impact category	S1: Windrow based	S2: EP-1000 based	S3: Sanitary landfilling	S4: Unsanitary landfilling
GWP100	1,143,615	412	2,123,677	3,874,117
FAETP	1865	0.525	6,570,043	6,619,467
HTP	108,866	38.2	657,228	617,623
TEP	511	0.18	4805	4649

The units for impact categories are given in the footnote of the table

GWP100: global warming potential (kg of CO_2-eq Mg^{-1} of waste), FAETP: freshwater aquatic toxicity potential (kg 1,4-DB-eq Mg^{-1} of waste), and HTTP: 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) the vicinity of water bodies, lakes, and rivers could result in aquatic, human, and terrestrial toxicities. FAETP measures the potential for eutrophication in freshwater ecosystems, which leads to oxygen depletion, loss of biodiversity, and water quality degradation. In a tropical city such as Dhaka, the urban areas often generate large amounts of runoff containing pollutants from open-dumped waste, sewage, and other sources, which can flow into nearby rivers, lakes, and wetlands. Eutrophication can severely affect the quality of freshwater resources used for drinking, recreation, and ecosystem services, which is a concern for densely populated cities. Results presented in Table 3 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 (6.57×10^5 kg 1,4-DB-eq Mg^{-1} of waste) and S4 (6.17×10^5 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.

2.5.3 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 is part of S2 and its whole facility is operated by solar power. Regarding windrow composting, it is essential to note that there are some negative aspects of the composting process as well [26]. 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 [26]. However, these are not usually acknowledged as additional greenhouse gas emissions as they are biogenic and part of the short-term carbon cycle [43]. The anaerobic approach includes methanogenic and denitrification processes during composting which lead to emissions of CH_4, nitrous oxide, and ammonia [44–46].

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 3). 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 emissions and also lead to odor problems. 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 [44]. 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 [26].

Global waste management techniques have improved manifolds with lesser environmental impact over the last few decades [47]. 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 [48]. Advanced pyrolysis and gasification showed more benefits in terms of energy recovery [5]. However, landfill is the most common practice in developing countries as a means of waste management and they are more prone to being 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 [49]. In urban centers in China alone, about 3.3 million to 5.6 million people are involved in informal recycling [50]. 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 the waste management process.

HTP assesses the potential harm to human health due to human exposure to heavy metals, pesticides, volatile organic compounds, and other toxic substances. It is understood that populous cities often experience high levels of air and water pollution, which can lead to human health risks such as respiratory illnesses, cancers, and developmental disorders. Further, the use of chemicals in construction, manufacturing, and other urban activities (e.g., pesticides, solvents) can contribute to human toxicity, especially for vulnerable populations (children, elderly, low-income communities). Therefore, in highly dense cities such as Dhaka, it becomes inevitable to consider HTP in an LCA analysis.

2.5.4 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 3). 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).

Most urban areas of developing countries with high concentrations of industry, manufacturing, and transportation often release toxic chemicals into the environment. This includes heavy metals (e.g., mercury, lead) and persistent organic pollutants (e.g., PCBs, dioxins). Additionally, improper waste management (e.g., landfill leachate, incineration) can release harmful toxins into air, water, and soil exposing city neighborhoods to high levels of environmental toxins due to proximity to industrial areas, waste disposal sites, or heavy traffic corridors. This may lead to chronic health effects over time, particularly in highly populated cities where exposure can be widespread.

2.5.5 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 are shown in Fig. 3. 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 (Fig. 3a, b). The least contribution during S1 was the energy use as well as for S2 that used solar-powered EP-1000 composting machine (Fig. 3b).

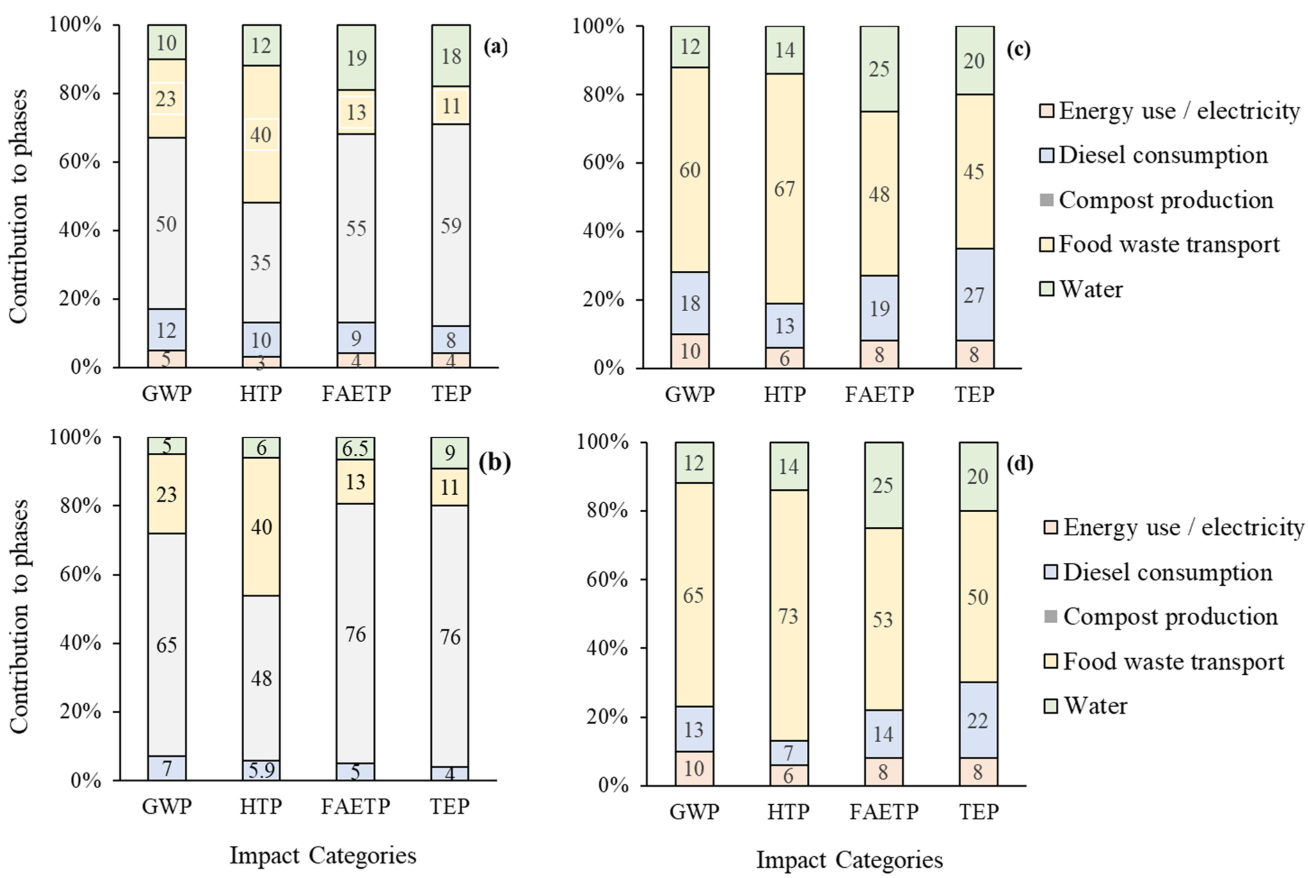

Fig. 3 **a** Percent contribution of various production systems inputs and outputs to the impact categories (GWP: global warming potential; HTP: human toxicity potential; FAETP: freshwater aquatic ecotoxicity potential; TEP: terrestrial ecotoxicity potential for waste management. **a** Scenario 1 of windrow composting, **b** Scenario 2 of EP-1000 machine composting, **c** Scenario 3 of sanatory 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 (Fig. 3c, d). 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 [51], 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 [52, 53], 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 [54]. The presented work considered ELCA and achieved comprehensive sets of results for waste management scenarios in DCC, Bangladesh. However, literature also showed that other waste management methods such as anaerobic digestion-based composting in combination with incineration can have the least environmental impact for several reasons including energy recovery [55]. Overall, the decentralized waste-to-compost facility lowers methane emissions, improves soil health, and may help lessen the urban heat island effect. In Dhaka, where space is typically limited and waste management infrastructure is overburdened, composting can drastically reduce waste volume, lower disposal costs, and contribute to a circular economy by completing the loop between organic waste generation and agricultural demands. Dhaka can manage waste management challenges while enhancing environmental sustainability and urban resilience by promoting composting at both the individual and municipal levels.

The results of a Monte Carlo analysis showed that the standard deviation for the values of environmental burdens was within the limit of being categorized as substantial uncertainty mentioned by IPCC (Table 4).

Monte Carlo analysis, used to analyze and quantify the uncertainties associated with each unit process, falls within the limits specified in the literature [56, 57]. The main causes of uncertainty are variability in input parameters, data variability, data gaps, assumptions, and subjective interpretation procedures such as effect assessment and normalization [58]. Based on the standard deviation values of the four scenarios, the values for unsanitary and sanitary landfill options were not within the limit mentioned by IPCC, which is 0.3 [59, 60]. Scenario 2 (EP-1000 based) presented the best option for MSW management with standard deviation values for all the environmental burdens being less than 0.3.

3 Conclusion

Given the fact that compost production from MSW management can generate high-quality organic fertilizer [61] and help avoid negative environmental impacts such as emission of harmful gases, odor, etc. [62], this study examined four waste management scenarios using software to assess the ELCA. 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 showed 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 solutions to better waste management and can have greater potential to have a positive environmental effect. However, the use of secondary data in LCA analysis of studies similar to this may conduct uncertainty analysis [59] while interpreting LCA results. Future research should focus on the efficacy of the decentralized composting facility with more indicators (including individual land use, eutrophication, and ozone layer depletion in addition to GWP, HTP, FAETP, and TEP) to facilitate implementation strategy for policymakers in profitable resource generation, environmental stewardship and in mitigating the problem of MSW. By implementing waste-to-compost a city can minimize the need for costly landfill and incineration facilities, resulting in decreased municipal waste management expenses. Composting promotes sustainable practices in local communities and has the potential to increase soil quality, which benefits urban gardening, landscaping, and small-scale agriculture.

Table 4 Overall result of a Monte Carlo analysis 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)

Environmental burdens	Mean	SD	Median	5% Percentile	95% Percentile
S1: Windrow based					
GWP100	47.8	1.34	47.9	45.7	50.1
FAETP	7.69	0.16	7.69	7.42	7.95
HTP	9.27	0.21	9.28	8.94	9.62
TEP	0.03	0.0007	0.03	0.03	0.03
S2: EP-1000 based					
GWP100	0.41	0.11	0.41	0.22	0.59
FAETP	1.20	0.41	1.21	0.52	1.85
HTP	1.07	0.36	1.08	0.47	1.65
TEP	0.0009	0.0003	0.0009	0.0004	0.001
S3: Sanitary landfilling					
GWP100	630,595	621	630,607	629,577	631,605
FAETP	1,946,412	1921	1,946,450	1,943,263	1,949,540
HTP	194,995	192	194,999	194,680	195,308
TEP	1424	1.40	1424	1421	1426
S4: Unsanitary landfilling					
GWP100	1,147,579	1172	1,147,610	1,145,562	1,149,497
FAETP	1,960,773	2004	1,960,826	1,957,326	1,964,050
HTP	182,949	186	182,954	182,627	183,255
TEP	1377	1.41	1377	1374	1379

The units for impact categories are given in the footnote of the table

GWP100: global warming potential (kg of CO_2-eq Mg^{-1} of waste), FAETP: freshwater aquatic toxicity potential (kg 1,4-DB-eq Mg^{-1} of waste), and HTTP: 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)

Local composting projects, like neighborhood compost centers, can also help to promote a sense of community, a circular bioeconomy, and the availability of new jobs.

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References

1. Menikpura SN, Gheewala SH, Bonnet S. Sustainability assessment of municipal solid waste management in Sri Lanka: problems and prospects. J Mater Cycles Waste Manage. 2012;14:181–92.
2. Kaza S, Yao L, Bhada-Tata P, Van Woerden F. What a waste 2.0: a global snapshot of solid waste management to 2050. World Bank Publications; 2018.
3. Sharma BK, Chandel MK. Life cycle assessment of potential municipal solid waste management strategies for Mumbai, India. Waste Manag Res. 2017;35(1):79–91.
4. Girotto F, Alibardi L, Cossu R. Food waste generation and industrial uses: a review. Waste Manage. 2015;45:32–41.
5. Yıldız-Geyhan E, Yılan G, Altun-Çiftçioğlu GA, Kadırgan MA. Environmental and social life cycle sustainability assessment of different packaging waste collection systems. Resour Conserv Recycl. 2019;143:119–32.
6. Bangladesh. World Bank; 2018. https://www.worldbank.org/bd
7. Alam O, Qiao X. An in-depth review on municipal solid waste management, treatment and disposal in Bangladesh. Sustain Cities Soc. 2020;52: 101775.
8. Waste Concern Technical Report Series: Bangladesh Waste Database. Waste Concern. 2014.
9. JICA. The study on the solid waste management in Dhaka city-clean Dhaka master plan. 2005.
10. Waste Database–Waste Concern. 2014.
11. Bahauddin KM, Uddin MH. Prospect of solid waste situation and an approach of Environmental Management Measure (EMM) model for sustainable solid waste management: case study of Dhaka city. J Environ Sci Nat Resour. 2012;5(1):99–111.
12. Hasan MR, Tetsuo K, Islam SA. Landfill demand and allocation for municipal solid waste disposal in Dhaka city—an assessment in a GIS environment. J Civ Eng. 2009;37(2):133–49.
13. Yasmin S, Rahman MI. A review of solid waste management practice in Dhaka City, Bangladesh. Int J Environ Protect Policy. 2017;5(2):19–25.
14. Ahsan A, Alamgir M, El-Sergany MM, Shams S, Rowshon MK, Daud NN. Assessment of municipal solid waste management system in a developing country. Chin J Eng. 2014;2014(1): 561935.
15. DNCC. Future vision of solid waste management in Dhaka North city. https://dncc.portal.gov.bd/. 2022.
16. What a waste Global Database | Data Catalog. What a Waste Global Database | Data Catalog. 2019.
17. United Nations. Sustainability | United Nations. United Nations. https://www.un.org/en/academic-impact/sustainability
18. Finnveden G, Hauschild MZ, Ekvall T, Guinée J, Heijungs R, Hellweg S, Koehler A, Pennington D, Suh S. Recent developments in life cycle assessment. J Environ Manage. 2009;91(1):1–21.
19. UNEP. Towards a green economy: pathways to sustainable development and poverty eradication. Sustainable Development Knowledge Platform. 2011.
20. Al-Rumaihi A, McKay G, Mackey HR, Al-Ansari T. Environmental impact assessment of food waste management using two composting techniques. Sustainability. 2020;12(4):1595.
21. Zhou Z, Tang Y, Chi Y, Ni M, Buekens A. Waste-to-energy: a review of life cycle assessment and its extension methods. Waste Manage Res. 2018;36(1):3–16.
22. Yadav P, Samadder SR. A critical review of the life cycle assessment studies on solid waste management in Asian countries. J Clean Prod. 2018;185:492–515.
23. Krishna IM, Manickam V, Shah A, Davergave N. Environmental management: science and engineering for industry. Butterworth-Heinemann; 2017.
24. Zurbrügg C, Drescher S, Rytz I, Sinha AM, Enayetullah I. Decentralised composting in Bangladesh, a win-win situation for all stakeholders. Resour Conserv Recycl. 2005;43(3):281–92.
25. Community Based Solid Waste Management in Bangladesh—Waste concern. 2001.
26. Pergola M, Persiani A, Pastore V, Palese AM, D'Adamo C, De Falco E, Celano G. Sustainability assessment of the green compost production chain from agricultural waste: a case study in southern Italy. Agronomy. 2020;10(2):230.
27. Shohan, MW. A case study on solid waste management in Dhaka city. Masters Thesis, Bangladesh University of Engineering and Technology, 2015.
28. ISO—Standards. ISO. https://www.iso.org/standards.html
29. Wernet G, Bauer C, Steubing B, Reinhard J, Moreno-Ruiz E, Weidema B. The ecoinvent database version 3 (part I): overview and methodology. Int J Life Cycle Assessm. 2016;21:1218–30.
30. Coulomb R, Dietz S, Godunova M, Bligaard T. Critical minerals today and in 2030. OECD Environment Working Papers. 2015.
31. Open source | openLCA.org. https://www.openlca.org/open-source/
32. Mizdrak A, Cobiac LJ, Cleghorn CL, Woodward A, Blakely T. Fuelling walking and cycling: human powered locomotion is associated with non-negligible greenhouse gas emissions. Sci Rep. 2020;10(1):9196.
33. Tilman D, Clark M. Global diets link environmental sustainability and human health. Nature. 2014;515(7528):518–22.
34. Bartzas G, Zaharaki D, Komnitsas K. Life cycle assessment of open field and greenhouse cultivation of lettuce and barley. Inform Process Agric. 2015;2(3–4):191–207.
35. Norris GA. The requirement for congruence in normalization. Int J Life Cycle Assessm. 2001;6:85–8.
36. Guinée JB, et al. Life cycle assessment: past, present, and future. Environ Sci Technol. 2010;45(1):90–6.
37. Hayashi T, van Ierland EC, Zhu X. A holistic sustainability assessment tool for bioenergy using the Global Bioenergy Partnership (GBEP) sustainability indicators. Biomass Bioenerg. 2014;66:70–80.
38. Blair SN, Cooper KH. Exercise | definition, types, principles, & health effects. Encyclopedia Britannica. 2024.
39. Itoiz ES, Gasol CM, Farreny R, Rieradevall J, Gabarrell X. CO2ZW: Carbon footprint tool for municipal solid waste management for policy options in Europe. Inventory of Mediterranean countries. Energy Policy. 2013;56:623–32.
40. Maria C, Góis J, Leitão A. Challenges and perspectives of greenhouse gases emissions from municipal solid waste management in Angola. Energy Rep. 2020;6:364–9.

41. US EPA. Global Non-CO2 GHG emissions: 1990–2030 | US EPA. Office of Atmospheric Programs, Climate Change Division. 2024.
42. Parvin M, Begum A. Organic solid waste management and the urban poor in Dhaka city. Int J Waste Resour. 2018;8(320):2.
43. Batjiaka R, Brown S. Creating topsoils and soil conditioners from biosolids and urban residuals. J Environ Qual. 2020;49(4):1020–31.
44. Brown S, Subler S. Article Composting and greenhouse gas emissions: a producer's perspective. BioCycle; 2007: 37–41.
45. Amlinger F, Peyr S, Cuhls C. Green house gas emissions from composting and mechanical biological treatment. Waste Manag Res J Sustain Circ Econ. 2008;26(1):47–60.
46. Boldrin A, Andersen JK, Møller J, Christensen TH, Favoino E. Composting and compost utilization: accounting of greenhouse gases and global warming contributions. Waste Manag Res J Sustain Circ Econ. 2009;27(8):800–12.
47. Mehta C, Sirari K. Comparative study of aerobic and anaerobic composting for better understanding of organic waste management: a mini review. Plant Archives; 2019: 44–48.
48. Malmir T, Ranjbar S, Eicker U. Improving municipal solid waste management strategies of Montréal (Canada) using life cycle assessment and optimization of technology options. Energies. 2020;13(21):5701.
49. Medina M. Solid wastes, poverty and the environment in developing country cities: challenges and opportunities. 2010.
50. Linzner R, Lange U. Role and size of informal sector in waste management—a review. Proc Inst Civ Eng Waste Resour Manag. 2013;166(2):69–83.
51. Society of Environmental Toxicology and Chemistry (SETAC). Guidelines for Life-Cycle Assessment. Environ Sci Pollut Res. 1994;1(1):55.
52. Güereca LP, Gassó S, Baldasano JM, Jiménez-Guerrero P. Life cycle assessment of two biowaste management systems for Barcelona, Spain. Resour Conserv Recycl. 2006;49(1):32–48.
53. Iriarte A, Gabarrell X, Rieradevall J. LCA of selective waste collection systems in dense urban areas. Waste Manage. 2009;29(2):903–14.
54. Rives J, Rieradevall J, Gabarrell X. LCA comparison of container systems in municipal solid waste management. Waste Manage. 2010;30(6):949–57.
55. Saer A, Lansing S, Davitt NH, Graves RE. Life cycle assessment of a food waste composting system: environmental impact hotspots. J Clean Prod. 2013;52:234–44.
56. Sharma T, Dasgupta D, Singh J, Bhaskar T, Ghosh D. Yeast lipid-based biofuels and oleochemicals from lignocellulosic biomass: life cycle impact assessment. Sustain Energy Fuels. 2020;4:387–98. https://doi.org/10.1039/C9SE00540D.
57. Bhonsle AK, Singh J, Trivedi J, Atray N. Comparative LCA studies of biodiesel produced from used cooking oil using conventional and novel room temperature processes. Bioresour Technol Rep. 2022;18: 101072. https://doi.org/10.1016/j.biteb.2022.101072.
58. Sheikholeslami Z, Ehteshami M, Nazif S, Semiarian A. The environmental assessment of tertiary treatment technologies for wastewater reuse by considering LCA uncertainty. Process Saf Environ Prot. 2022;168:928–41. https://doi.org/10.1016/j.psep.2022.10.074.
59. Patel K, Singh SK. Sustainable waste management: a comprehensive life cycle assessment of bioethanol production from agricultural and municipal waste. Environ Sci Pollut Res. 2024;31(39):51431–46.
60. Patel K, Singh SK. Assessing the sustainability of municipal solid waste management using life-cycle analysis. In: Proceedings of the Institution of Civil Engineers-Waste and Resource Management (Vol. 175, No. 3, pp. 64–74). Thomas Telford Ltd. 2022.
61. Aziz R, Chevakidagarn P, Danteravanich S. Life cycle sustainability assessment of community composting of agricultural and agro industrial wastes. J Sustain Sci Manag. 2016.
62. Mizdrak A, Cobiac LJ, Cleghorn CL, Woodward A, Blakely T. Fuelling walking and cycling: human powered locomotion is associated with non-negligible greenhouse gas emissions. Sci Rep. 2020. https://doi.org/10.1038/s41598-020-66170-y

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