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Life cycle assessment of municipal solid waste management in Kathmandu city, Nepal – An impact of an incomplete data set

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ABSTRACT

Few studies have been done about engineered facilities related to waste collection, treatment, and disposal in the waste management sectors across Nepal. The decision support system is not well established, resulting in poor planning and execution of waste management. Available data for performing a life cycle assessment (LCA) is limited. We used an LCA model to investigate waste management options for Nepal's capital, Kathmandu. We also tested the hypothesis that exclusion from the LCA model of variables for which there was no data would make no difference in the management rankings. The assessment was based on three scenarios: business as usual, including collection, transportation, and landfilling; recycling; and conjunctive disposal comprised of composting and landfilling. The LCA methodology we used includes detailed unit processes and quantified values of various resources and emissions to compute the impact level on the environment. The contribution of the collection, transportation, landfilling, and recycling was calculated as global warming potential, acidification potential, eutrophication potential, and fuel energy consumption for each scenario. Scenario 3 ranked higher than scenarios 1 and 2 based on available data. The results were based on the environmental burden of metric tons of municipal solid waste handled at landfills, regardless of what was recycled and composted. Scenario 3 yielded minimum environmental impacts and was a cost-efficient option. Using a range of literature values for the missing variables, it was shown that the excluded variables made no difference in the scenario rankings. The study successfully employed the LCA as a decision-making tool in waste management in Kathmandu, which can be useful for other cities in developing countries.

Author statement

Mohan B. Dangi: Visualization, Methodology, Data curation, Interpretation of results, Writing- Original draft preparation, Reviewing, Editing.

Om B. Malla: Conceptualization, Investigation, Writing- Original draft preparation, Software.

Ronald R.H. Cohen: Writing- Reviewing, Editing, Calculation, Validation, Software.

Nawa R. Khatiwada: Supervision.

Samir Budhathoki: Calculation, Writing- Reviewing, Editing.

1. Introduction

Waste has been an inevitable byproduct of human civilization, mostly arising from social and economic aspects of people's lives (Gautam, 2011). Based on the rate and quantity of waste generation, its types, and composition, alternative methods could be selected to manage waste streams. Environmental assessment tools like life cycle assessment (LCA) can and have been employed to integrate data on the characteristics of the waste, the environmental impacts of the various wastes, and the advantages and disadvantages of waste management protocols (Khorasani et al., 2012; SETAC, 2020). LCA has proven to be useful to evaluate the performance of municipal solid waste (MSW)

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management (Assamoi & Lawryshyn, 2011). The LCA "cradle to grave" approach could be effective in choosing the proper tool to help solve the MSW problem we observe in Nepal (Barton et al., 1996; Khorasani et al., 2012). LCA includes not only a product within the system, but also services, processes, or activities (Bahor et al., 2010).

Also, life cycle inventory (LCI) is one component of an LCA. The entire suite of material and energy resources can be used as inputs and the products and emissions that are the outputs need to be recognized and computed in the LCI (Abeliotis, 2011). Ibanez-Fores et al. (2021) used LCA, LCI, and life cycle impact assessment (LCIA) tools to achieve waste recovery goals in the medium- and long-term in a Brazilian city. LCIA permits the characterization and mitigation of various problematic substances. For example, after the emissions from an uncontrolled disposal facility have been quantified, it is important to calculate in what way those environmental emissions will affect the surrounding. JRC (2011) comprehensively provided a compilation of the key impacts coming from open dumps, emission to every impact category, and appropriate indicators to come up with the associated impacts. Ferrari et al. (2021) also took a similar approach to utilize LCA and LCI along with enterprise resource planning in an industry environment. Other studies that used LCA for waste handling, to recommend the effective method for sustainable solid waste management (SWM) and energy recapture include Arena et al. (2015), Dong et al. (2018b), and Jensen et al. (2016). Arena et al. (2015) found that, in treating residual MSW in Europe, incineration has less environmental burden than gasification among the impact categories. Likewise, using the LCA, Dong et al. (2018a) established that incineration plants have a lower environmental impact than pyrolysis and gasification. Several recent studies (Dastjerdi et al., 2021; Ferrari et al., 2021; Ghasemi-Mobtaker et al., 2020; Ibanez-Fores et al., 2021; Khanali et al., 2021; Levis et al., 2017; Mostashari-Rad et al., 2021; Nabavi-Pelesaraei et al., 2020, 2021) have also used LCA, LCI, and LCIA tools to successfully manage MSW.

Wang et al. (2020) stated that LCA was effective in addressing important issues such as greenhouse gas (GHG), more accurately known as radiatively active gas, emissions from MSW operations because of enhanced waste collection, treatment, recycling, and the prevention of waste. Dastjerdi et al. (2021) and Evangelisti et al. (2015) stressed that LCA is an upcoming instrument to assess the environmental impacts of a waste treatment operation. LCA can be helpful in decision-making concerning acidification, global warming, environmental toxicity, and human impacts at various phases of waste management (Dastjerdi et al., 2021; Ripa et al., 2017; Tunesi, 2011). Other contemporary uses of the LCA tool include evaluating environmental harm due to irrigation systems during barley production in Iran (Ghasemi-Mobtaker et al., 2020), analysis of environmental impacts associated with horticultural inputs (Mostashari-Rad et al., 2021), examination of multi-objective energy optimization and emission generation in walnut production in Iran (Khanali et al., 2021), assessment of the likelihood of using solar technologies in the production of sunflower in Iran (Nabavi-Pelesaraei et al., 2021), and investigation of eco-efficiency variations in paddy production in Iran (Saber et al., 2021).

In the present context, while the studies of life-cycle environmental emissions from sanitary landfills are increasing, there have been few studies covering the uncontrolled disposal of waste (Levis et al., 2017). Here are a few such studies: GHG emissions from landfill sites by Banar et al. (2009) for Eskisehir, Turkey; Batool and Chuadhry (2009) for Lahore, Pakistan; Manfredi and Christensen (2009) for Denmark; Thanh and Matsui (2013) for Da Nang, Vietnam; Oyoo et al. (2014) for Kampala City, Uganda; and by Guan et al. (2015) for Zhejiang Province, China.

There has been limited research and a lack of public knowledge about the long-term impact of uncontrolled dumping in Nepal and other locations (Dangi, 2009; Dangi et al., 2006, 2017; Levis et al., 2017). In this paper, we used LCA procedures to understand the impact of uncontrolled dumping of MSW and the effectiveness of a variety of SWM approaches in Kathmandu city, also known as Kathmandu, the capital of Nepal. (See the basic information about the study area along with Fig. S1 under Supporting Information of the manuscript.)

We assess the life cycle of MSW management in Kathmandu. We then compared the results with alternative management methods and relate our findings to recent studies (Iqbal et al., 2020; Khandelwal, Dhar, et al., 2019; Khandelwal, Thalla, et al., 2019; McDougall et al., 2001, 2008; Nabavi-Pelesaraei, Bayat, Hosseinzadeh-Bandbafha, Afrasyabi, & Berrada, 2017; Nabavi-Pelesaraei, Bayat, Hosseinzadeh-Bandbafha, Afrasyabi, & Chau, 2017; Nabavi-Pelesaraei et al., 2020; Silva et al., 2021; Taşkın & Demir, 2020). Our paper first examines the current waste management practices in Kathmandu in detail and then evaluates the environmental impact scenarios, including metrics on global warming, acidification, eutrophication, and energy consumption related to SWM. The focus of this study is to characterize the environmental impacts of existing SWM in Kathmandu city and compare the results to those from three scenarios of SWM described in subsection 2.1. The three scenarios that we developed are SWM systems that include various MSW processing and/or disposal methods. The scenarios were developed and then compared based on their environmental impacts, i.e., global warming potential (GWP); acidification potential (AP); eutrophication potential (EP); and total fuel energy consumption (FEC) for collection; transportation; and management of MSW from the point of waste generation to landfilling.

The goal is to apply LCA to select solutions to the long-term problems of MSW disposal, thereby addressing health issues; water and air pollution; and coming up with environmentally sound waste disposal in Nepal.

Generally, compositing is considered one of the major techniques to manage organic waste (Fadhullah et al., 2022) and it can serve as an alternative to landfill for recycling organic waste as it is cost-effective and less complicated (Ajaweed et al., 2022). Organic solid waste normally consists of higher organic carbon content, which can release carbon resulting in greater GHG emissions into the atmosphere (Bian, Zhang et al., 2022). An appropriate method of managing organic solid waste needs to be adopted to prevent carbon loss, mitigate GHG emissions, and maintain carbon neutrality (Mulya et al., 2022).

A technique with a lower carbon footprint can be an effective approach for organic SWM to control GHG emissions (Huang et al., 2021). Several methods, i.e., landfilling, anaerobic digestion, composting, incineration, thermal conversion, etc., have been widely used to manage organic solid waste (Huang et al., 2022; Ye et al., 2023). However, composting along with an aerobic and anaerobic reaction occurring within the soil can convert the biodegradable organic waste in soil fertilizers to stable compost formation (Ajaweed et al., 2022). A study suggested that composting not only accounts for plant productivity and soil quality, but it also leads to higher crop yields reducing waste volume and eliminating pathogens and weeds (Vlachokostas et al., 2021). Conversion of organic portion of MSW into an earthy, humus like substance by the action of bacteria and microbes can be broadly categorized into two different phases, degradation and humification (Wei et al., 2022). Carbon losses occur during degradation; however, humification can sequester carbon in the soil (Huang et al., 2022). Composting for the most part is another method to manage organic sold waste preventing GHG emissions to meet the global carbon balance.

It is important to note that the data set, the only one available at the time, did not include historical data concerning the direct emissions from composting and energy recovery and indirect emissions from processes like collection and transportation. Therefore, one of the goals of this study was to find out if the incomplete data had any significant impact on the modeling results and decision-making. Examination of the literature suggested that these missing variables would likely have no impact on the ranking of the scenarios in our study. Thus, we were determined to discover whether this was the case in Kathmandu, Nepal. The ultimate contribution of the study is to provide effective, economically sound, and data driven decision-making tools for SWM in low-income countries.

Our study is divided into seven parts: introduction (current section), materials and methods, results and discussion, environmental impacts, policy implications, conclusions, and recommendations.

2. Materials and methods

The European Union regulations on applying LCA require a hierarchical system based on four levels: reduction of solid waste generation, recovery of material, recovery of energy, and landfill disposal (Feo & Malvano, 2008). The phases of LCA procedures include goal and scope definition, LCI, LCIA, and interpretation (Clift et al., 2000). The goal and scope definition describes the purpose and extent of a study to identify the intended audience and to describe the problem that will be addressed. Then there will be a comparison of alternative solutions. While the LCI focuses on a qualitative analysis of mass and energy fluxes, the LCIA is directed to evaluate the magnitude and significance of potential environmental impacts. Then there is an interpretation of the results from the previous phases. This interpretation connects the goal and scope definition with other findings to reach conclusions and recommendations for the system of study (Assamoi & Lawryshyn, 2011). To complete the study, we used three scenarios to compare the alternatives for MSW management in Kathmandu city by employing the specifications of the International Organization for Standardization (ISO) series 14,040 about LCA (ISO, 2006). The three scenarios consist of business as usual (BAU), including collection, transportation, and landfilling; recycling; and conjunctive disposal procedure comprised of composting and landfilling. These scenarios are included in Fig. 1. Similar approaches were also utilized by other researchers (Nabavi-Pelesaraei, Bayat, Hosseinzadeh-Bandbafha, Afrasyabi, & Berrada, 2017; Nabavi-Pelesaraei, Bayat, Hosseinzadeh-Bandbafha, Afrasyabi, & Chau, 2017; Nabavi-Pelesaraei et al., 2020; McDougall et al., 2008). This paper describes the LCA of SWM in Kathmandu, which was developed into four phases. These phases were described by McDougall et al. (2001 and 2008) and Nabavi-Pelesaraei et al. (2020).

The three scenarios included in this study with system boundaries are described here.

2.1. Scenarios

2.1.1. Scenario 1—Business as usual, including collection, transportation, and landfilling

It consists of three steps: collection, transportation, and landfilling of MSW. This illustrates the current status of MSW management undertaken by Kathmandu. About 10% of total waste is recycled in Kathmandu (Bhattarai, 2003; Dangi et al., 2009). Since plastics, paper, and glass make up 11%, 9%, and 5% of the total waste, respectively, another 15% of the recyclable material is still being landfilled in Kathmandu (Waste composition of the study is mentioned in subsection 3.2 later.). Given the actual recycled amount was so little, recycling was not considered in Scenario 1.

2.1.2. Scenario 2— Recycling

It assumes a system where recyclable waste, primarily paper, plastics, and glass, i.e., 25% of the total MSW, is recovered and recycled while the remaining waste is transported to the landfill. Scenario 2 is assessed to find the possibility of improving the existing SWM in Kathmandu.

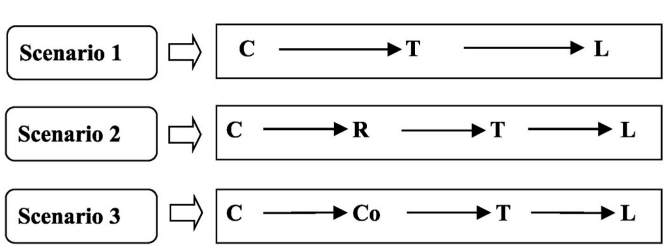

Fig. 1. Scenarios considered in the study (C = collection, T = transportation, L = landfilling, R = recycling, and Co = composting).

2.1.3. Scenario 3— Conjunctive disposal comprised of composting and landfilling

Conjunctive disposal systems consist of composting and landfilling that employ aerobic as well as anaerobic digestion of 63% of the organic waste before landfilling. Therefore, it only assumes that the remaining 37% would end up in the landfill. These are common practices of MSW treatment methods in Europe (Ozeler et al., 2006).

2.2. Data collection

The fact sheet including day-to-day waste generation and operation and management statistics for MSW in Kathmandu was collected from the Solid Waste Management Section of the Environment Management Department of the city. The data includes the total waste collected by Kathmandu city in 2011. The breakdown of the data consists of the population, waste stream characteristics, collection rate, composition by weight, and operational conditions of landfills. The percentage of landfill input, waste processing capacity, composting rate, recycling rate, fuel energy consumption cost in Nepali Rupee (NR) per metric ton (mt), and distance to the landfill site in kilometers are used in this inventory. (A US dollar was equivalent to NR 87.64 at the time of the study.) Also, the city provided a monthly log of fuel energy consumption used in SWM activities. The FEC included: the types of fuel used, and the total amount of money expended on the fuel. Secondary data were collected through a detailed literature survey and review using multiple online databases and applicable research papers on LCA of SWM from South Asia as well as other developing countries.

2.3. LCA framework

2.3.1. Goal and scope definition

As described toward the end of section 1 above, the goal of the study was to characterize the environmental impacts of existing MSW management in Kathmandu city and compare the results to those from three alternate scenarios of MSW management. The three scenarios that we developed are SWM systems that include various MSW processing and/or disposal methods. The scenarios were developed and then compared based on their environmental impacts, i.e., GWP, AP, EP, and total FEC for collection, transportation, and management of MSW from the point of waste generation to landfilling.

To characterize waste generation and environmental impacts, it is necessary to define a functional unit as the total waste generated in a given geographical region for a period, i.e., expressed in kg or mt per year (McDougall et al., 2001; Nabavi-Pelesaraei, Bayat, Hosseinzadeh-Bandbafha, Afrasyabi, & Berrada, 2017). In this study, the functional unit is expressed as the total amount of waste generated in Kathmandu in a year: 168,265 mt as per the total collection of solid waste. This is generated by households, commercial establishments, industries, and nearby villages and collected on road surfaces.

Another requirement for LCA studies is system boundaries. In the case of a cradle-to-grave approach inherent to the LCA procedures, the cradle is known as the moment when material loses its value from an owner's perspective, and the grave is recognized when the waste is landfilled and becomes inert as emission to air or water (McDougall et al., 2001). The direct emissions resulting from landdfilling of MSW are included in this study.

There were some limitations to the study due to a lack of historical data concerning the direct emissions from composting and energy recovery and indirect emissions from processes like collection and transportation. Budgetary limitations precluded our ability to collect the data ourselves. We hypothesized that the omission of this data would have no significant impact on the ranking of the scenarios or selection of the most efficacious management tools. The emissions by energy consumption during the collection, transportation, and landfilling of MSW and transportation of fuel itself is a small part of the total emissions from the system (Eriksson et al., 2005). Also omitted from the study are the impacts of waste in the working environment, casualties during waste handling, and the impact of the odor.

We tested the hypothesis that the missing data for direct emissions from composting and energy recovery and indirect emissions from processes like collection and transportation would have minimal impact on the ranking of the scenarios. This was tested by obtaining quantitative values of these variables from the literature and establishing a range of values for the variables. The LCA model was run in multiple modes.

a) Without the direct emissions from composting and energy recovery and indirect emissions from processes like collection and transportation.
b) With high literature values both of indirect and direct emissions from composting and energy recovery and indirect emissions from processes like collection and transportation.
c) With high literature values of indirect and low values of direct emissions from composting and energy recovery and indirect emissions from processes like collection and transportation.
d) With low literature values of indirect and high values of direct emissions from composting and energy recovery and indirect emissions from processes like collection and transportation.
e) With low literature values of indirect and low values of direct emissions from composting and energy recovery and indirect emissions from processes like collection and transportation.

2.3.2. Life cycle inventory

LCI includes the collection of data for all mass and energy inputs and outputs, followed by calculation to complete the stage (McDougall et al., 2008). The net result from the LCI is the quantification of all environmental interventions including input and outputs (Coventry et al., 2016; Nabavi-Pelesaraei, Bayat, Hosseinzadeh-Bandbafha, Afrasyabi, & Berrada, 2017). These inputs and outputs consist of "energy and material balances, atmospheric emissions, waterborne emissions, solid waste, and other releases for the entire life cycle of a product, process or activity (SAIC, 2006, p. 19)." The justifications for omitting some inputs and outputs are explained in subsection 2.3.1 above.

The data under discussion in this paper also refers to the data collected and reported in subsection 2.2 above. However, the fuel energy consumption cost does not account for the fuel used by private organizations, non-governmental organizations, and community-based organizations engaged in SWM for the collection, transportation, and management of MSW.

Similarly, LCI was used as an important step to determine the flow of mass and energy inputs and outputs in MSW management by Goulart Coelho & Lange (2018) where they conducted characterization and generation of MSW. Other studies also provide emission information about the resource consumption and pollutants to produce electricity from each energy source (Flury & Frischknecht, 2012; McDougall et al., 2001; Pehnt, 2006).

The remaining information on MSW management such as recycling, composting, energy recovery, and landfilling were taken from relevant literature (Alam et al., 2008; Bhattarai, 2003; Chen et al., 2016; Dangi, 2009; Dangi et al., 2009, 2011, and 2017; Energypedia, 2020; Iqbal et al., 2014; Karki, 2015; Kuo & Dow, 2017; LaRiviere, 2007; Larsson & Sahlen, 2009; Larsson et al., 2010; MOUD, 2015; Parajuly et al., 2018; Pokhrel & Viraraghavan, 2005; Shrestha et al., 2014; Trindade et al., 2018; Wichmann et al., 2006). The potential heat content (HC) was determined using the heat value of MSW components as shown in Eq. (1) (USEPA, 2006).

$$HC = f_i \times HV_i \tag{1}$$

where,

HC is heat content, f_i is the fraction of component i, and HV_i is the heating value of component i.

The calculated heat content in (one) Million British Thermal Units per hour or MBTU was converted to megawatts of electricity using the conversion factor of a 1-MW hour of electricity is equivalent to 3.4 MBTU (USEIA, 2020). The average household demand for electricity for lighting in Nepal of 2 kW h (Energypedia, 2020) was used to calculate the number of households receiving electricity by 1 MW h.

2.3.3. Life cycle impact assessment

In this life cycle impact assessment, the results of the life cycle inventory are converted into a format applicable to management needs (Khorasani et al., 2012). There are internationally documented protocols and standardization for the performance of an LCIA (Hofstetter et al., 2000). To perform LCIA, a unique system and standardization that have global acceptance are not presented because currently, historical MSW management data does not exist (Hofstetter et al., 2000). As a result, the scientific methods for long-term assessment are not presented. The approach of "lower is better," used since the 1990s, is also considered in this section of the study (Khorasani et al., 2012). This approach assumes that all values from one type of stress or cumulative environmental burdens are gathered without considering the place and time of stress or whether the levels of stress are more or less than the threshold values. Also, due to innate characteristics of various stress types, they may cause detrimental changes to the environment (White et al., 1997). Therefore, the LCIA is done according to the ISO (2006) standard through the concept of indicators as outlined in Fig. 2.

The three environmental impact categories, i.e., GWP, AP, and EP were chosen and included in this study. The GWP was calculated using the Intergovernmental Panel on Climate Change (IPCC, 2021) waste model that estimates the amount of CH_4 generated from MSW and converted using the factor of 21 to CO_2 equivalent multiplied by total waste landfilled in each scenario as shown in Eq. (2).

$$GWP = [MCF(x) * DOC(x) * DOCF \times F * 16/12]\ Gg\ CH_4\ Gg\ waste^{-1} \tag{2}$$

where,

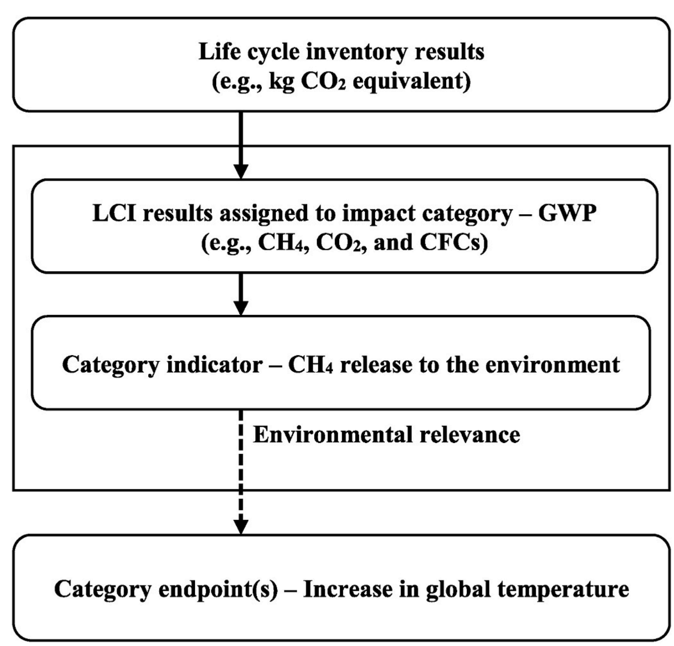

Fig. 2. Concept of indicators for life cycle impact assessment (McDougall et al., 2001).

GWP = Global warming potential,
MCF(x) = Methane correction factor in year x (fraction),
DOC(x) = Degradable organic carbon in year x,
DOCF = Fraction of DOC dissimilated,
F = Fraction by volume of methane in gas generated from landfill, and
16/12 = Conversion from C to CH_4.

The IPCC (2021) waste model, which accounts for CH_4 emissions from open dumping, is significant for the first 40 years after waste disposal and was used to calculate GWP.

Acidification potential was calculated as the product of the Nielsen and Hauschild (1998) landfill model referring to the H_2S emitted from one mt of waste and converted to SO_2 equivalent and total waste landfilled in each scenario. Eutrophication potential was reported in NO_3^- equivalents referring to the highest contribution by landfilling found in a similar study in Sri Lanka (Menikpura et al., 2012). The fuel energy consumption data was obtained from Kathmandu city as the total amount of monetary value expended to purchase the fossil fuel, i.e., petrol, diesel, and kerosene combined used to collect, transport, and manage waste and multiplied to total waste handled through landfilling in each scenario.

2.3.4. Interpretation

The final stage of LCA, i.e., interpretation, includes the review of the first three phases. Comparative analysis was carried out using a spreadsheet program based on a given functional unit. The results were described as environmental impact categories backed up with justification and reasoning.

A site visit to Sisdol Landfill, the landfill serving Kathmandu from June 5, 2005, to July 2022, by the second author took place in May 2019 and the first author visited both Sisdol Landfill and the newly constructed Banchare Danda Landfill on February 21, 2023. The visits were useful to validate the existing SWM scenario for Kathmandu. In any LCA study, the final step in impact assessment is the valuation of weighting methods that do not have any formal scientific significance (Bishop, 2000; Ozeler et al., 2006), especially when the impact categories (GWP, AP, and EP) can vary and are dependent on processes, time, and local geography (Al-Salem & Lettieri, 2009). Therefore, this study was more focused on the comparison of impacts or environmental burdens by the quantity of waste managed via landfilling, rather than waste recycled, and composted for each scenario developed.

It is important to note that this paper is not meant to be conclusive but to serve as a foundation on which further research can be built. The research primarily is based on secondary data obtained from Kathmandu city, and so lacks some primary data for calculations. In addition, we wanted to examine if the model could be useful for solid waste disposal in Kathmandu even though the available data set did not include historical data concerning the direct emissions from composting and energy recovery and indirect emissions from processes like collection and transportation. The literature (Bian, Chen, et al., 2022; Yaman, 2020) suggests that the missing data will have little impact on the model scenario ranking, and therefore on the SWM decision-making, which is presented in detail under subsection 4.5 later. The functional system boundary of this LCA study does not include long-term emissions from landfills, where potential emissions continue for approximately 100 years (Eriksson et al., 2005).

3. Results and discussion

3.1. Current SWM practices

Earlier efforts of SWM in Kathmandu date back to 1919 when the city first established a sanitary office (Dangi, 2009; Thapa & Devkota, 1999). Since its inception, the entity has been organizing solid waste and sanitation practices in the city and its territory (Dangi, 2009). In Kathmandu, a whistle-blow and door-to-door collection practice are in place, involving private sector operators, non-governmental organizations, and community-based organizations. Nearly all waste is collected unsorted and unprocessed, while only a small portion is source segregated (Chhetri, 2011). Unfortunately, Kathmandu has not been able to establish an appropriately engineered sanitary landfill site after the city's last landfill, Gokarna Landfill, was closed in 1996, resulting in illegal dumps and disposal along the banks of Bagmati River and Bishnumati River (Dangi et al., 2009; Tuladhar, 1996). The temporary landfill, Sisdol, when it first opened on June 5, 2005, was financially and technically supported by the Japan International Cooperation Agency, and was supposed to only last for three years (Chhetri, 2011; Dangi et al., 2009). Another temporary landfill, Aletar, located adjacent to Sisdol, was utilized until the end of 2011, Sisdol Landfill was ultimately closed after more than 17 years of its life with multiple closures and reopening in July 2022, and Banchare Danda Landfill, two km west of Sisdol, proposed as a long-term landfill with 20 years of holding capacity, came into operation also in July 2022. A field visit by the first author on February 21, 2023, affirmed that solid waste is deposited with little care and no soil cover in Banchare Danda Landfill, hazardous hospital waste can be found scattered throughout the working face of cell 1 in Banchare Danda, the two leachate treatment ponds are nearly full in capacity, the leachate recirculation unit is not functioning, and the massive concrete platform built adjacent to the landfill for waste sorting is not in operation. At any given time nearly 100 informal workers would be scavenging waste haphazardly in Banchare Danda during its operation after the waste is unloaded in the face of cell 1, putrefying garbage along with dead animals are left uncovered throughout the surface of cell 2 of closed Sisdol Landfill, and local villagers were badly impacted by odor and vector problems.

3.2. Waste generation and composition

The population of Kathmandu is 1,003,285 (CBS, 2010) and the average unit generation of solid waste is 0.17 kg $person^{-1}$ d^{-1}. The daily waste generation was found to be 480 mt d^{-1} at the end of 2011 (KMC, 2011). Household waste comprises more than two-thirds of the total solid waste (330 mt d^{-1}) in Kathmandu and commercial, street, and nearby village waste each contributes 50 mt d^{-1}.

Understanding the quantity of waste generated and its characteristics are crucial in designing an effective SWM plan in a city. The waste generation rate and its composition vary with population growth, lifestyle choices, economic activities, and seasonal events. The Solid Waste Management Act 2011 (2021) has prescribed the separation of solid waste into at least organic and inorganic wastes. Inorganic waste can be further segregated into plastics, paper, glass, textile, metals, rubber and leather, inert materials (sand and stones), and others. The data from Kathmandu city shows that the major portion of MSW is organic waste at 63% (KMC, 2011). See Fig. 3. Plastics and paper comprise the key portions of the inorganic waste, while metals and rubber and leather each had the smallest share at about 1% of total MSW.

3.3. Waste collection

The residents of Kathmandu have one of three options to drop off their MSW: at designated areas in the city directly on the roadside, in a container, or in one of the collection vehicles in operation each morning (Larsson & Sahlen, 2009). Various types of motorized and non-motorized vehicles and equipment are used to collect the waste and subsequently transport it to the transfer station and then to the landfill (Alam et al., 2008).

The Solid Waste Management Section of Kathmandu city has 890 sweepers, 150 drivers, 38 administrative staff, 25 mechanics, 24 metro polices, four engineers, five junior engineers, two officers, a department head, and 120 other staff (KMC, 2011). Likewise, the Environment Management Department of the city has 1047 sweepers, 100 drivers, 50

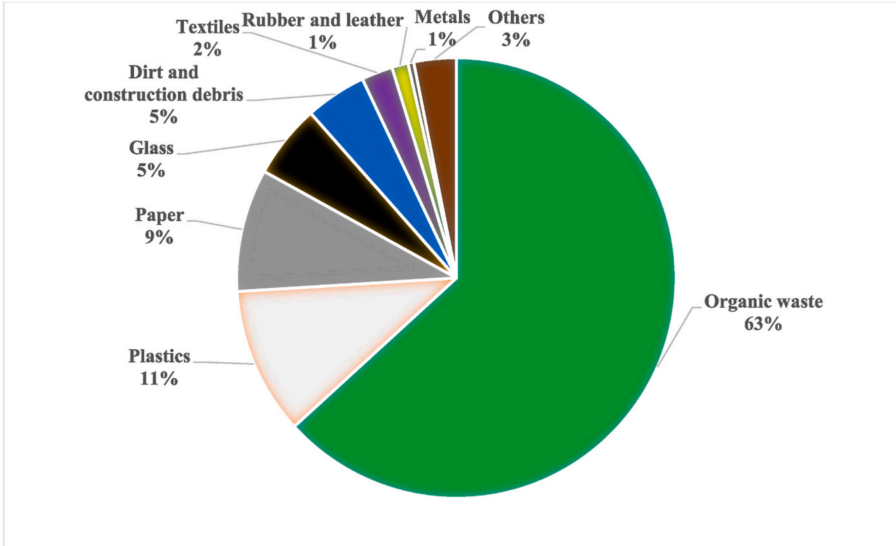

Fig. 3. Composition of municipal solid waste in Kathmandu city (KMC, 2011).

mechanics, 50 administrative workers, six community motivators, and nine engineers (Nippon Koei Co Ltd. & Yachiyo Engineering Co Ltd., 2005). (The staff may be cross-listed and counted twice as the Solid Waste Management Section is part of the Environment Management Department in the city. For details, see Fig. S2 under Supporting Information of the manuscript.) In Kathmandu, sweepers account for 51% of the city's MSW budget, and the remaining budget is allocated in the following manner: collection (33%), transfer station (3%), transportation (5%), and landfill management (8%) (Dangi et al., 2009).

Of the 461 mt d^{-1} of MSW collected (96% of MSW generated), 77.6% or 358 mt is collected from designated areas on the roadside, 13.1% or 60 mt comes from specific containers located in different areas of the city, and the remainder is gathered from door-to-door collections (KMC, 2011). However, another study (ADB, 2013) estimated a collection efficiency of 86.9% of the total waste generated. At Teku transfer station in Kathmandu city, some separation of valuable MSW is conducted, after which the MSW used to be transported to Sisdol Landfill until July 2022 and presently to Banchare Danda Landfill for disposal.

3.4. Recycling

Kathmandu city does not have a recycling operation for paper, plastics, or rubber and leather. However, the Community Mobilization Unit (CMU) of the city promotes recycling and reuse. The CMU together with Nepal Recyclable Entrepreneurs Association has established scrap collection centers where recyclable waste can be sold (Larsson & Sahlen, 2009). Informal workers locally known as *kavadiwalas* are also involved in the waste pickup at the source (Dangi et al., 2009). Using bicycles, these hawk cyclers collect waste from door-to-door in Kathmandu. While some of the traditional workers are equipped to process their recycled waste, others ship the recyclables to India for further handling (Larsson et al., 2010). The recycling activity also includes *kavadiwalas* scavenging valuable waste goods at the transfer station, streets, municipal containers, and landfill sites and then selling the goods to the recycling centers, locally known as *kavadi* shops (Dangi et al., 2009, 2017). A study (MOUD, 2015) also reported about 300 scavengers were involved in segregating the waste at the landfill site. Overall, the reuse and reprocessing of waste by local manufacturers or shipment to industries in India contribute to the recycling effort in Nepal (Dangi et al., 2009; Larsson et al., 2010). However, according to another study (Dangi, 2009), careless handling of waste occurs when personal economic benefits take priority over efficient, planned SWM. This poorly planned and executed activity inhibits the organized improvement of SWM. It is important to note that *kavadiwalas* and informal scavenging manage approximately 10% of the total MSW in Kathmandu (Bhattarai, 2003; Dangi et al., 2009). Although formal recycling is still missing in Kathmandu (Dangi et al., 2017), the MSW goes through the attempts of multi-stage material recovery from the point of generation to even after its dumped in the landfill (Parajuly et al., 2018), thus indicating a potential diversion of at least 25% of total MSW from landfills.

3.5. Composting

The Solid Waste Management Act 2011 (2021) of Nepal directs the local government to construct and operate compost plants to process organic waste. Kathmandu city neither issues directives nor operates compost plants to reduce the volume of the organic portion of MSW. However, the 19th Municipal Council meeting decided to distribute compost bins for residents at a 50% subsidized rate. It provided 1500 compost bins in 2011–12 and 1739 in 2013–14. A total of 3239 compost bins distributed for three years is inadequate when compared to over a million residents in Kathmandu at the time (MOUD, 2015). Most recent data show similar figures. In the fiscal year 2020–21, 446 compost bins were sold by Kathmandu city to its residents at a largely subsidized cost, 570 were sold in the fiscal year 2021–22, and the city is planning to distribute another 884 bins in the upcoming fiscal year. While the city claims to have distributed more than 10,000 compost bins since 2002, the numbers are still dismal with an average distribution of 500 bins a year and the fact that the city has no record of the proper use of the bins nor their conditions (Kathmandu Metropolitan City, 2022). In addition, the transfer station was built for segregating the waste collected and composting the organic waste, but it is not in operation due to managerial issues and a lack of infrastructure (MOUD, 2015).

Dangi et al. (2011) suggested considering the composting of organic waste based on the rate of waste generation and composition with a detailed study of waste management strategies. Previous studies on MSW composition have shown that organic waste makes up most of the total waste. The organic components of the waste are in a range of 60%–71% of the total MSW generated (ADB, 2013; Alam et al., 2008; Dangi et al., 2011; Karki, 2015). The studies have recommended implementing waste segregation and handling of waste at the source to divert as much waste as possible from landfills.

In developing countries, the scenarios for SWM in rural areas are equally alarming as it is in urban communities, where there is a lack of scientific strategies to manage waste (Das et al., 2019). Unlike urban areas, composting is the most practiced and accepted SWM technology in rural areas (Narayana, 2009). In many developing nations, bio-waste is considered the major fraction of the MSW stream in rural areas (Mihai & Ingrao, 2018). One of the studies affirmed that proper management of critical parameters and source segregation of bio-waste results in home composting as a more practical and economically viable option in rural areas (Van Fan et al., 2016). Currently, different modern and large-scale composting is commonly practiced in various rural areas as a part of waste management practice. Windrow composting facilitated with aeration is extensively used in vegetable culture in rural areas to recycle solid waste, i.e., both biodegradable and organic, for waste management (Gavilanes-Terán et al., 2016). Solid waste production in cities is higher than in rural areas, where rapid urbanization and lifestyle changes can alter waste production proportions. Another study indicated that 40% of the waste dumped in a landfill in city areas consists of biodegradable materials (Manios, 2004).

In brief, studies have suggested that composting of different kinds is more accepted as a SWM treatment option in rural areas (Das et al., 2019; Mihai & Ingrao, 2018). However, several energy recovery technologies, i.e., waste to energy, commercially are more prevalent and their urgency is considered in city areas not only to cope with the various environmental challenges associated with waste management but also to meet the energy demand of the global population.

3.6. Energy recovery

Energy recovery in MSW management has dual advantages: minimizes the waste landfilled and produces useful energy through incineration or bio-gasification (Trindade et al., 2018). It was suggested that MSW can be used to produce electricity through incinerators with a conversion efficiency of 20–30% (McDougall et al., 2008). Although incineration is more suitable for MSW with non-biodegradable material and low moisture content (Trindade et al., 2018), studies (LaRiviere, 2007; Shrestha et al., 2014) have recommended a method, (USEPA, 2006), to determine the heat content using the heat values of MSW components as shown in Eq. (1) in subsection 2.3.2 above. It's been realized that the power generation by burning MSW is difficult because of the variability of the waste stream composition and the moisture content. Heat generation needs to be carefully controlled to be uniform, and that is difficult with MSW.

The results suggest that the MSW of Kathmandu city has the potential to produce 9.28 MBTU of heat content, which is theoretically equivalent to 2.7 MW of electricity. See Table 1. If the organic waste is digested aerobically or anaerobically or handled with other forms of MSW management, the rest of the MSW can produce 3.98 MBTU of heat content, equivalent to about 1.16 MW of electricity, i.e., enough to light around 580 households (Energypedia, 2020; Shrestha et al., 2014).

Table 1
Average heat value of the dry component of MSW in Kathmandu adapted from USEPA (2006).

Dry component of MSW	Average heat value (MBTU US ton^{-1})	Average heat value (MBTU mt^{-1})[a]	MSW heat content in Kathmandu (MBTU mt^{-1})
Organic wastes	7.6	8.37	5.296
Plastics	22.6	24.91	2.690
Paper	6.7	7.38	0.666
Glass	0.1	0.11	0.006
Metals	0.7	0.77	0.003
Textiles	13.8	15.21	0.349
Rubber	26.9	29.65	0.27[b]
Leather	14.4	15.87	
Total			9.28

Note.
[a] 1 mt = 1.10231 US ton.
[b] The value of 0.27 accounts for the combined heat content of rubber and leather in Kathmandu, which was calculated using an average of the heat values of rubber and leather from column 3 of the table.

Anaerobic digestion of organic waste combined with livestock manure can be more efficient in producing biogas. This is a sustainable and environmentally friendly energy option (Iqbal et al., 2014). Also, anaerobic digestion can yield 90.6 m^3 of methane per [US] ton of organic waste (Kuo & Dow, 2017) producing an estimated 29,103.4 m^3 of methane in ideal condition from organic portion of waste collected in Kathmandu city in a day (KMC, 2011). Collection and containment of biogas are important and expensive components of recycling, and the overall costs must be incorporated into the decision-making about the waste management processes.

3.7. Landfilling

The landfilling of waste is one of the most common, and least expensive methods to manage MSW. The required skill levels of workers in landfills are low. Landfilling can be suitable for developing countries (Chen et al., 2016). A study (Pokhrel & Viraraghavan, 2005) reported that more than 72% of the total waste generated in Kathmandu city ends up in landfills. For landfilling to be effective, it must be done using internationally accepted safety and sanitary procedures. Kathmandu city spent three times the average cost for landfilling compared to other cities in South Asia. Kathmandu city was not able to practice standard sanitary procedures during landfilling (Dangi et al., 2009).

With the combination of the closure of a compost plant on the premises of the Teku transfer station, the banning of informal waste scavenging there, and the lack of formal recycling and material recovery; an increasing amount of MSW is ending up in landfills (MOUD, 2015). While the Solid Waste Management Act 2011 (Nepal) lists the provision to run a landfill site designed to avoid adverse impacts on the surrounding environment, the MSW in Kathmandu city was dumped into the Sisdol Landfill without appropriate mitigating measures as described earlier. The Sisdol Landfill site proposed for three years' use during the construction of a permanent landfill had operated for more than 17 years as noted above. The Sisdol Landfill lacked proper engineering design and provisions for expansion (MOUD, 2015). The site seemed to have accepted a level of MSW a lot larger than the holding capacity of 275,000 mt of MSW (Shrestha et al., 2014). The proper closure and post-closure care of the Sisdol Landfill must be addressed. Constructing any new landfill will require a design that minimizes the human and environmental impact of long-term use. Landfilling can be used in conjunction with other methods like recycling or material recovery, energy recovery, and composting to avoid adverse effects, i.e., contamination of nearby water sources and soil that can last up to 25 years after the closure of the facility (Nabavi-Pelesaraei, Bayat, Hosseinzadeh-Bandbafha, Afrasyabi, & Chau, 2017; Shrestha et al., 2014; Wichmann et al., 2006). The research reported in this paper suggests that less than 10% of the total MSW would only be discarded and landfilled (Dangi, 2009), hence would have potentially increased the life expectancy of the Sisdol Landfill by five times. The status and effectiveness of the current landfill, Banchare Danda, were mentioned in subsection 3.1 above.

4. Environmental impacts

As mentioned in subsection 2.1 above, we have developed three scenarios or SWM alternatives that are quantified according to the various impacts on the environment. These results are combined with the fuel energy consumption associated with the different scenarios presented in Table 2.

Based on the data gathered at the life cycle inventory stage, Table 2 shows the results assuming the total quantity of waste generated per year is landfilled; the next scenario, column 2, assumes that some of the waste is recycled. Column 3 includes waste that is composted. Scenario 1 represents business as usual where landfilling is the only option for the disposal of 168,265 mt of MSW per annum. The waste that can be

Table 2
Quantity of landfilled that could be recycled and composted for each of the developed scenarios.

Scenario type	MSW landfilled (mt yr^{-1})	MSW recycled (mt yr^{-1})	MSW composted (mt yr^{-1})
BAU	168,265		
Recycling	126,199	42,066	
Composting	62,258		106,007

recycled in Scenario 2 is 42,066 mt per year. The organic waste that can be used for composting is 106,007 mt annually.

Similar to Scenario 1, Mathioudakis et al. (2022) also employed subsequential modeling technique to further examine BAU, where they discovered that the scenario can have several benefits if implemented properly. In addition, the study suggested there would be significant reduction of emissions under BAU when the food waste would be source segregated. Therefore, the environmental benefits of Scenario 1 were found to be rather significant (Mathioudakis et al., 2022). MSW comprises of both biomass (food waste, paper, grass clippings, leather, etc.) and fossil fuel materials (rubber, plastics, glass, ceramics, metals, etc.). The biomass products are degradable and the fossils fuels are hard to decompose (Ayodele et al., 2018).

Like Scenario 2, a study suggested that recycling could be one of the dominant SWM methods, where the discarded waste can be recycled and reused, lowering the consumption of fossil fuels. This eventually can result in reduced GHG emissions (Shah et al., 2021). As recycling rate increases carbon emission decreases or vice versa (Liu, Tan, et al., 2020).

Composting is a widely used practice to manage organic solid waste, which can bring down landfill gas emission as it can convert the degradable waste to energy (Fadhullah et al., 2022; Mor & Ravindra, 2023). Anaerobic digestion could be the best method for decomposition of kitchen waste compared to other existing treatment options with the lowest environmental impacts and higher energy recovery (Shih et al., 2021). Keng et al. (2020) suggested that in larger scale operations, composting, being an aerobic process, will be more convenient as it will not require the advanced reduced condition. Different studies have different arguments on each of the processes of composting and landfilling; however, when these processes applied in conjunction can limit the GHG emissions with the lesser environmental impacts much like the findings of our study.

4.1. Global warming potential

The IPCC (2021) guidelines suggest that the Sisdol Landfill site can be categorized as a deep and unmanaged dumping site, and thus has a high potential for methane emissions. Furthermore, the MSW consists of a large fraction of biodegradable waste, 63% organic waste which leads to a greater share of degradable organic carbon. Also, the subtropical climate of Sisdol Landfill additionally favors methanogenesis. The IPCC (2021) waste model was used to calculate GWP as included in Eq. (2) in subsection 2.3.3 above.

Based on the characteristics of waste and the conditions of the Sisdol Landfill site, the calculated IPCC default values for Eq. (2) are: $MCF(x) = 0.5$ (value for partially aerobic landfill site), $DOC(x) = 0.174$, $DOCF = 0.5$, and $F = 0.5$. The IPCC waste model estimated 29 kg of CH_4 as the total potential methane generation from one mt of MSW landfilled (UNFCCC, 2020). The conversion factor of 21 kg carbon dioxide equivalent was used per kg of CH_4 (DEFRA, 2012). The CO_2 generation is included in subsection 4.5 below.

4.2. Acidification potential

Acidification potential is defined as a pollutant's capacity to form many H^+ ions from acidifying contaminants like H_2S, SO_x, NO_x, NH_3, etc. Which consequently oxidize to form acids with significant impacts on both flora and fauna (Nabavi-Pelesaraei, Bayat, Hosseinzadeh-Bandbafha, Afrasyabi, & Berrada, 2017). It is derived as H^+ ions produced per kg substance relative to SO_2 equivalent (Baumann & Tillman, 2004). Although the transportation factor is one of the main contributors to acidification potential, it's not considered in this study while only AP due to landfilling is considered.

A landfill model estimated that 0.65 kg of H_2S is emitted from a mt of waste landfilled (Nielsen & Hauschild, 1998). Using this model, the overall acidification potential in Sisdol is 1.22 kg of SO_2 equivalent per mt of MSW landfilled. In addition, recycled paper, cardboard, and plastics may decrease the acidification potential (Nabavi-Pelesaraei, Bayat, Hosseinzadeh-Bandbafha, Afrasyabi, & Berrada, 2017); however, the recycling rate in Kathmandu city is only about 10% (Bhattarai, 2003; Dangi et al., 2009).

4.3. Eutrophication potential

Eutrophication can be defined as the phenomenon where excess nutrients, such as nitrogen and phosphorus species, are washed from the environment into terrestrial and aquatic ecosystems and result in algae blooms and a general increase in biomass in a waterway (Banar et al., 2009). Nitrogen, one of the major elements found in landfill waste, is considered a primary contributor to eutrophication along with phosphorus. The nitrogen is carried through leachate and runoff to the nearest water resource, i.e., *Kolpu Khola* (river). The estimated eutrophication potential for a mt of MSW landfilled is 16.42 kg of nitrate equivalent (Menikpura et al., 2012). However, the eutrophication potential can be controlled by careful engineering design of the landfill and regular monitoring of the water movement through the landfill. The goal is to prevent leachate and runoff from reaching the stream.

4.4. Fuel energy consumption

As mentioned in subsection 3.3 above about the MSW budget in Kathmandu city, the majority of fuel costs account for 49% of the budget attributed to collection, transfer and transport, and operation and management of the landfill.

The total fuel cost including diesel and petrol for the collection, transportation, and management of waste for the fiscal year 2011–12 was approximately NR 745,251 (KMC, 2011). The collection and transportation of waste does not have a fixed route but a fixed number of trips with a fixed amount of fuel (Alam et al., 2008). The figures suggest that Kathmandu city spends NR 4.42 per mt of MSW transported and landfilled for fuel cost. This amount doesn't account for the fuel charges by private companies during the collection and transportation of MSW.

4.5. Impact of variables not included in the database

We tested the hypothesis that the LCA model was not impacted significantly by the lack of data for several variables by including a wide range of values for the variables in the models from the literature.

The results of the model calculations for the three scenarios are shown in Table 3. The total values for each of the three scenarios provide a comparison of the environmental burdens and the total cost of fuel consumed during the collection, transportation, and management of MSW. Table 3 also provides the results of including a wide range of values from the literature for variables that were not in the database.

The composting scenario shows the least impact on the environment based solely on database values.

Adding the high and low values from the literature in several combinations to the calculations shows minimal impact on the scenario ranking of environmental input.

5. Policy implications

A goal of creating effective public policy is to arrive at a decision that

Table 3
Calculations for ranking the three scenarios, where the totals from the LCA models are in bold font.[a]

Results from 3 scenarios without missing variables

Scenarios	GWP (kg CO2 eq. mt MSW-1 landfill-1 yr-1)	AP (kg SO2 eq. mt MSW-1 landfill-1 yr-1)	EP (kg NO3- eq. mt MSW-1 landfill-1 yr-1)	FEC (total fuel consumed in NR mt MSW-1 landfill-1 yr-1)	Total
BAU	1.02 E+08	2.05 E+05	2.76 E+06	7.45 E+05	1.06 E+08
Energy recovery	7.81 E+07	1.57 E+05	2.11 E+06	5.68 E+05	8.10 E+07
Composting	**3.77E + 07**	7.55 E+04	1.02 E+06	2.74 E+05	**3.91E + 07**

Results from 3 scenarios with high-range literature values for indirect and direct missing variables

Scenarios	GWP	AP	EP	FEC	Total	High Indirect	High Direct	Total
BAU	1.02 E+08	2.05 E+05	2.76 E+06	7.45 E+05	1.06 E+08	7.38 E+04	0.00 E+00	1.06 E+08
Energy recovery	7.81 E+07	1.57 E+05	2.11 E+06	5.68 E+05	8.10 E+07	7.38 E+04	8.03 E+05	8.19 E+07
Composting	**3.77E + 07**	7.55 E+04	1.02 E+06	2.74 E+05	**3.91E + 07**	7.38 E+04	8.03 E+05	**3.99E + 07**

Results from 3 scenarios with high-range literature values for indirect and low-range values for direct missing variables

Scenarios	GWP	AP	EP	FEC	Total	High Indirect	Low Direct	Total
BAU	1.02 E+08	2.05 E+05	2.76 E+06	7.45 E+05	1.06 E+08	7.38 E+04	0.00 E+00	1.06 E+08
Energy recovery	7.81 E+07	1.57 E+05	2.11 E+06	5.68 E+05	8.10 E+07	7.38 E+04	5.55 E+02	8.11 E+07
Composting	**3.77E + 07**	7.55 E+04	1.02 E+06	2.74 E+05	**3.91E + 07**	7.38 E+04	5.55 E+02	**3.91E + 07**

Results from 3 scenarios with low-range literature values for indirect and high-range values for direct missing variables

Scenarios	GWP	AP	EP	FEC	Total	Low Indirect	High Direct	Total
BAU	1.02 E+08	2.05 E+05	2.76 E+06	7.45 E+05	1.06 E+08	2.88 E+04	0.00 E+00	1.06 E+08
Energy recovery	7.81 E+07	1.57 E+05	2.11 E+06	5.68 E+05	8.10 E+07	2.88 E+04	8.03 E+05	8.18 E+07
Composting	**3.77E + 07**	7.55 E+04	1.02 E+06	2.74 E+05	**3.91E + 07**	2.88 E+04	8.03 E+05	**3.99E + 07**

Results from 3 scenarios with low-range literature values for indirect and high-range values for direct missing variables

Scenarios	GWP	AP	EP	FEC	Total	Low Indirect	Low Direct	Total
BAU	1.02 E+08	2.05 E+05	2.76 E+06	7.45 E+05	1.06 E+08	2.88 E+04	0.00 E+00	1.06 E+08
Energy recovery	7.81 E+07	1.57 E+05	2.11 E+06	5.68 E+05	8.10 E+07	2.88 E+04	5.55 E+02	8.10 E+07
Composting	**3.77E + 07**	7.55 E+04	1.02 E+06	2.74 E+05	**3.91E + 07**	2.88 E+04	5.55 E+02	**3.91E + 07**

Note.
[a] The table shows the results from calculations for the ranking of the three scenarios without the variables that were missing from the data set, to compare with the results from the LCA scenarios that included a wide range of literature data for the missing variables. The models, scenarios, and totals are in bold font. The values used for the direct–low range came from Yaman (2020). The values for the direct–high range and indirect-high range are from Bian, Chen, et al. (2022).

combines environmental, economic, and social components (Al-Salem & Lettieri, 2009). There are few, if any, rigorous LCA studies that have been conducted in Nepal, particularly concerning SWM; therefore, such studies are crucial to establishing an informed understanding of environmental burdens and costs associated with managing MSW in Kathmandu city. A publication (Khandelwal, Thalla, et al., 2019) identified the lack of LCA in SWM studies in the central region of India and emphasized the importance of social, economic, and psychological factors in SWM. Another publication (Khandelwal, Dhar, et al., 2019) mentioned the necessity of using an LCA to come up with an SWM hierarchy and reported that there has been only one LCA study in Nepal. Even then, the study (Singh et al., 2014) is slightly outdated and stressed landfilling heavily and left room for other options. Our study has the objective of setting a foundation for further and more intensive, extensive, and complete efforts to produce an LCA that can be used for MSW management decision-making in Nepal. Such studies will also lead to the establishment of databases that will aid decision-making processes and help elected officials take suitable environmental measures.

Additionally, the appropriate policy influences the residents' behaviors which requires them to have the proper knowledge of waste classification and environmental protection at the regional level (Villalba et al., 2020). The waste classification behavior will change residents' attitudes and assist them in characterizing and classifying waste before disposal, arousing awareness towards environmental protection (Liu, Osewe et al., 2020). Various factors like socioeconomic, institutional, temporal, and cultural aspects, etc. Can also affect waste quantity management and composition at regional levels as it varies accordingly based on locations (Villalba et al., 2020). A study performed in Jiangsu, China demonstrated the essence of education toward environmental protection as it pertains to SWM in rural areas (Liu, Osewe et al., 2020). Also, environmental protection awareness incorporates the benefits of classifying and collecting waste at the regional level on a daily basis (Fami et al., 2019; Mihai & Grozavu, 2019).

There are other recent studies that have similar policy objectives. For example, it's been suggested that recycling papers, plastics, metals, and glass can reduce the GWP by 50% as using recycled materials to produce plastics and papers consume less energy than producing them using raw materials (Nabavi-Pelesaraei, Bayat, Hosseinzadeh-Bandbafha, Afrasyabi, & Berrada, 2017). Also, recycling replaces raw materials and advances environmental sustainability (Nabavi-Pelesaraei et al., 2020).

We have included the emissions from the collection, transportation, and management of waste in landfills (Nabavi-Pelesaraei, Bayat, Hosseinzadeh-Bandbafha, Afrasyabi, & Chau, 2017) by using values found in the literature. We examined the effects of the emissions from the collection, transportation, and management of waste in landfills by executing the LCA model with a range of values found in the literature. The addition of the literature values for the missing data had little impact on the ranking of the scenarios based on their emissions to the environment. Even without performing an LCA, it is obvious that MSW management problems can be overcome by executing better landfill design; methane extraction from landfills; and use of methane as an alternative to fossil fuel.

In the past, people dumped their garbage and trash on the street or on the floodplains of the Bagmati River, in Kathmandu. The waste would be washed down to the Bagmati River flood plains. Often, pigs were released on the flood plains to separate the garbage from the trash. Pig manure combined with MSW contributed to the severe pollution that was apparent in the river. Sustainable SWM done in the most efficient, economical fashion would have dramatic impacts on the environmental conditions in Kathmandu.

The results of this study indicate the need for sustainable SWM in Kathmandu, that the approach must consider a conjunctive disposal system with composting and landfilling to reduce environmental impacts (AP, EP, and GWP). This excludes external factors like the inefficient collection system, low public participation, landfill location, and operational improvements. A well-thought-out integrated planning and capacity-building initiative in SWM backed by steady financial support could help alleviate the waste management and pollution problems in Kathmandu (Gautam, 2011). Additionally, the use of LCA along with proper waste characterization, recycling, and reduction—including reuse and composting for different types of wastes—and appropriate landfilling is crucial for a successful SWM operation.

6. Conclusions

This study was conducted to evaluate the use of LCA for SWM decision-making for Kathmandu city. An LCA model was run for each of three alternative SWM scenarios. LCA models were run with a wide range of literature values for missing data from the Kathmandu city data set. This is one of the few studies conducted for Kathmandu city using LCA.

The major findings of the study include.

1.) The current practice or Scenario 1 results in the highest global warming potential and is considered harmful in terms of other environmental impacts; 2.) Scenario 3 is the best alternative for lowering the contribution to climate change, eutrophication potential, and fuel energy consumption. This results in reduced environmental impacts and lower operating costs; 3.) Scenario 2 gives environmental impacts in between scenarios 1 and 3, thus becoming the second-best option; and 4.) Direct emissions from composting, energy recovery costs, and indirect emissions from collection and transport had little impact on the ranking of the environmental mitigation scenarios.

The findings suggest that Scenario 3 had the lowest potential for environmental impacts and is more cost-effective in terms of fuel energy consumption compared to the other scenarios. The outcome is influenced by the large quantities of organic waste that can be composted, resulting in the reduction of GWP. Overall, the results support the proposition that LCA can be applied to an integrated SWM operation as an environmental tool to support decision-making processes and the development of policy in Nepal.

7. Recommendations

These are the recommendations for sustainable SWM in Kathmandu based on our preliminary study.

a. The Solid Waste Management Section in Kathmandu city can focus on formally organizing recyclable materials recovery to help reduce the amount of waste disposed of in landfills and save landfill space, which will reduce the amount of national income spent on landfilling and reduce environmental burdens.
b. Because of the high quantities of organic waste in MSW in Kathmandu, almost two-thirds of the total waste, converting this waste to compost and biogas through aerobic and anaerobic processes may minimize the quantities of waste being deposited in landfills. This approach should be a priority.
c. The approach taken in our study should serve as an example for the development of appropriate integrated SWM options suited for local conditions. This approach has the potential to aid in the development of a successful implementation of waste management strategies, not just in Kathmandu, but in other Nepali municipalities as well.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.habitatint.2023.102895.

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