



# Application of Life Cycle Framework for Municipal Solid Waste Management: a Circular Economy Perspective from Developing Countries

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## Abstract

Municipal Solid Waste (MSW) management has been a long-standing problem for many cities in developing countries. Urbanization, population growth, and excessive demand for resources caused significant waste related environmental and socio-economic problems in cities. Integration of policy decisions with actionable targets and management of economic and environmental extremes were common challenges to achieving sustainable waste management strategy. Circular economy is a concept that has been evolved with sustainable resource management perspective adopted in this study to support scientific decision-making process for urban planners and policymakers. Life Cycle Assessment (LCA) is a framework to assess the environmental impacts of waste life cycle ranging from waste generation, transportation, treatment, and end disposal. This study used the LCA framework to evaluate the impact of MSW management of a selected local authority in Colombo, Sri Lanka, to identify the environmental impact of four (04) proposed scenarios in comparison with the Business-As-Usual (BAU) scenario. Environmental impacts were calculated using global warming potential in terms of greenhouse gas emissions and short-lived climate pollutants. The results revealed that management of MSW within the local authority boundary by integrating recycling, incineration, and sanitary landfill (3:8:1 ratio) offered the highest positive impacts (− 121.84 kg of CO<sub>2</sub> eq./ton) while BAU scenario caused the highest negative impacts (250.97 kg of CO<sub>2</sub> eq./ton) in comparison with selected scenarios. Moreover, incineration, sanitary landfill, recycling, and anaerobic digestion contributed to emission savings and energy generation. LCA framework was used to identify the composition of MSW for suitable technologies as well as to evaluate the efficiency of existing management mechanisms within a local authority. Evaluation was used to understand the holistic picture of multiple management options to support policymakers in the decision-making process. This framework can be used as a benchmarking tool and bridging concept between the waste management policy and local action plans, which is an important step towards achieving a circular economy for developing countries.

**Keywords** Municipal solid waste · Life cycle assessment · Environmental impacts · Circular economy

## Introduction

Municipal solid waste (MSW) management is an important service offered by local governments to ensure environmental quality and health and safety of the citizens. However, due to the rapid population growth, uncontrolled urbanization, and poor governance, MSW is considered an environmental, socio-economic, and political problem in many developing countries [1]. For instance, an open dumping site in Sri Lanka collapsed in 2016, revealing the short-sighted, unsustainable waste management strategies [2, 3]. While most of the decisions in MSW management are driven by political and economic terms [4–6], waste composition, socio-economic, and environmental impacts are given limited attention during this process. Due to land scarcity factors, urban planning agencies became responsible for the ownership of waste disposal sites in Sri Lanka such that waste management was not only a matter of economics or environment, but also a spatial planning problem. As a result, land-based, end-disposal strategies, and cost minimization alternatives have created a waste management dilemma for urban planners. However, waste minimization through reducing, reusing, and recycling of waste strategies is considered a potential solution while maintaining economic and social benefits to the society as a whole [7]. The importance of adopting waste hierarchy-management and minimizing burden on landfills were used as potential methods in developed countries [8–10]. However, the importance of closed loop waste life cycle was less studied and adopted in the context of developing countries. In addition, comparison of scientific and non-scientific strategies on waste management is a timely need for developing countries to tackle the rising challenges of urbanization, energy demand, and economic growth in cities. Therefore, it is important to link the practitioners and policy makers to view the waste management beyond materialistic values, towards long-term sustainability perspectives.

The circular economy is a concept aimed at the restoration and regeneration of material cycles while minimizing waste as an end of use strategy [9, 11]. Identification of waste hierarchy and evaluation of positive and negative implications in the process is a prerequisite towards this aim [7, 12]. The circular view focuses on the balance between economic growth and environmental quality in an optimum manner by deviating from linear consumption patterns (make-use-waste) to circular behavioral changes (make-use-renew) [13–15]. Rapid urbanization and unprecedented growth of rural-to-urban migration not only stimulate the economic activity in cities but also put pressure on limited natural resources ranging from water, food, and air. According to Lacy et al. [16], recent technological advancements and growing scarcity of natural resources pose an opportunity to move towards the circular economy by integrating zero waste strategies, use of recyclable materials, and commitments towards recyclable packaging. Waste management was considered an environmental problem in the past and it has been identified as a socio economic and financial problem by many cities to innovate long term actionable targets for sustainability [11, 17]. This shows the potential for adopting circular economic targets at the city level than at the individual scale. However, cities in developing countries face multiple challenges in achieving such targets due to fragmented responsibilities and limited integration of economic goals towards socio-ecological benefits [18]. Moreover, a mismatch between national-level policy decisions and local level action plans reveals the lack of incentives for achieving circularity in the waste management sector [19, 20]. Another problem in urban waste governance is the lack of benchmarking measures or performance criteria to evaluate the environmental, economic, and social impacts of the existing practice. Local authorities driven by technical motives often adopt actions like increasing the collection fleet of MSW,

expanding the capacity of end disposal sites, and searching for available lands to dispose of the rising demand of waste which are simply linear in nature. However, this study provides a framework for developing resource-oriented circular economic policy dialogue to address the rising waste demand in cities. Environmental impacts-based benchmarking can then link with economic criteria to support decision making at the local authority level.

Life Cycle Assessment (LCA) is a scientific framework used to evaluate the environmental impacts of a product or service from its origin to final disposal [5, 6, 21–25]. LCA assesses the impacts of MSW at the generation, transportation, processing, and end disposal stages as critical steps to understanding multi-layered impacts. In the context of a circular economy, the efficiency in consumption and production is vital in creating a closed-loop of resource circulation [25]. Therefore, LCA has been adopted by multiple disciplines to evaluate resource management from the perspectives of specific products, processes, and services. Saidani et al. [26] studied the sustainability and circularity of design-based projects, while Atanasova et al. [27] proposed nature-based solutions for the cities through water and waste management, food production, energy efficiency, and system recovery aspects. LCA has been widely applied in the context of urban services to achieve sustainability through shifting from linear to circular pathways of resource management. Prabhu, Shrivastava, and Mukhopadhyay [18] used LCA approach in the energy sector to assess the circularity in solar photovoltaic usage while Lee and Jepson [23] used LCA to identify the impacts on the water cycle in desalination process to understand the sustainability perspective. However, specific product-oriented assessment provided limited attention to the aggregate level of impact to the environment in an urban or regional scale. To make decisions on circularity of resource use, it is important to identify the resource pathways from waste generation point to the final disposal site in cities [28]. Moreover, best practices in resource management were evident in developed countries and the potential in developing countries was given limited attention in the LCA research. Therefore, it is crucial for developing countries to assess the waste life cycle and development of strategies for the circular economy due to increased population growth and waste generation [29].

Developing countries face continuous challenges related to waste management and economic growth due to fast economic growth trajectories [17]. Collection efficiency of MSW in the least developing countries was 39% in 2018 while it was 51% for lower middle-income countries [20]. In Sri Lanka, the overall MSW collection efficiency is placed as low as 27% in which Municipal Councils reached 51% while urban councils collected 17% of total generated waste in 2018 [30]. Management of MSW not only involves efficiency in governance but also the demand management of waste generation as well. COVID-19 pandemic and induced shocks have aggravated the economic impacts while challenges on utility services such as waste management faced severe implications. One of the key features in the assessment of waste management strategies in Sri Lanka is the high priority on end disposal methods in terms of technical and financial feasibility [2, 31, 32]. However, ignorance of environmental and socio-economic impacts in the steps leading to the final disposal of waste could lead to detrimental effects on society [33]. The limited attention on waste minimization strategies and circular economy-oriented pathways makes this an aggravated problem in developing countries like Sri Lanka. Therefore, this study delivered a scientific assessment framework to understand the positive and negative impacts of the MSW life cycle to support city-level decision-making. Although the LCA concept was widely used to assess the environmental impacts, limited research has applied it in the synthesis stage of MSW management. This study used the LCA framework (1) to assess the effectiveness of alternative waste management scenarios to support emission-based approaches over financial criteria, and (2) to evaluate its potential for deriving optimum use

of available resources in local authorities as a crucial step towards sustainability. Moreover, LCA framework can be used as the benchmark decision making criteria to recognize the waste management directives towards a circular economy by initiating homegrown solutions for local authorities in developing countries.

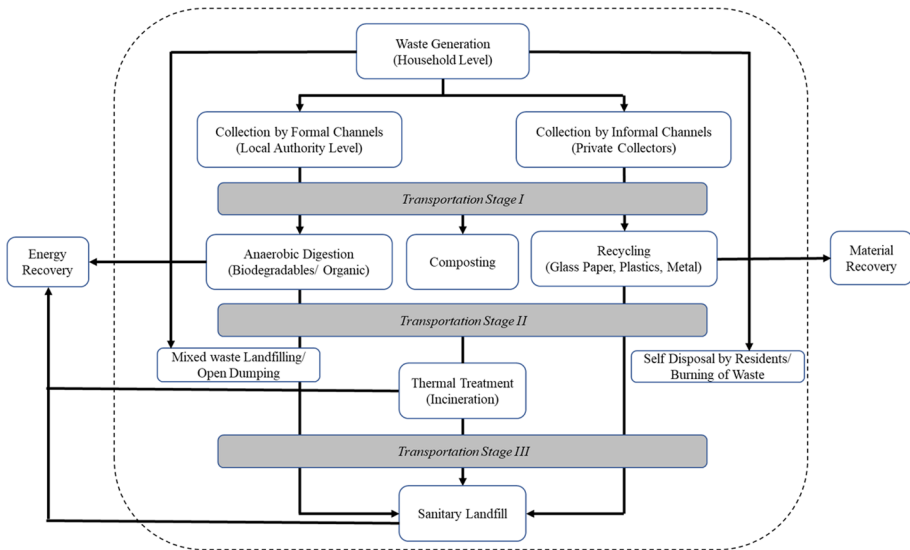
## Literature Review

### MSW Management Process and Assessment

Traditionally, waste management decisions were driven by economic costs and returns. However, new knowledge and modern technology exposed pathways to identify and simulate direct and indirect impacts from different perspectives [24, 34]. Waste management strategy in many developing countries is usually determined by the cost, land requirements, availability of expertise, reliability, and convenience of the facilities available [33, 35]. Moreover, decision makers at local authorities depend on cost minimization and other non-scientific methods in selecting the MSW management strategy where potential future impacts were sector biased in nature. The lack of coordination with policy decisions and real ground scenarios and limited collaboration with national to local level institutions are increasingly challenging for waste management sector. For example, technical guidelines provided by Central Environmental Authority (CEA) in Sri Lanka have limited control over local authority level decision-making and regulation due to socio-political, legal, and financial barriers [36]. In this context, an objective, measurable, and collaborative platform to assess the impacts of existing waste management practices at the local authority level can solve multiple issues related to technology, location, and resource management in the developing countries.

Recently, sustainability considerations and technological improvements have caused pressure for long-term solutions to focus on environmentally responsible, economically viable, and socially acceptable strategies [37–39]. Reduction of human health impacts and environmental pollution controls were key objectives in managing solid waste [40] due to various diseases and pollution in many urban areas. Breukelman, Krikke, and Löhr [20], identified the lack of a holistic diagnostic approach for the waste management process in developing countries as a key reason for failures in resource management while Luttenberger [10] revealed the transition towards a circular economy by divergence from end disposal methods like sanitary landfilling. However, to absorb such frameworks, it is vital to understand the life cycle of waste and appraisal of impacts to understand the required changes. Environmental impacts can be used as the baseline to assess the positive and negative implications of each waste management step in cities. The key stages of the typical waste management process and the environmental impacts are shown in Fig. 1.

MSW management strategies vary from country to country or city to city due to different economic, environmental, and social status-co and impacts [7, 41]. Open dumping of waste is the common practice for many developing countries [42], whereas poor management practices have created waste management a national level problem in countries like Sri Lanka [43]. Therefore, a systematic framework could assist the selection strategy for MSW with strong logical explanations and statistics [44]. Generally, waste management plans consider sustainability and social considerations, and sometimes, decisions derived from various tools can be contradictory due to differences in used criteria [21, 40]. Therefore, the type of tools used for the assessment will depend on the contextual needs and



**Fig. 1** Waste management process and its by-products

level of treatment required. The cheapest option would not be the best option in MSW management since the environmental damages caused by such an operation could not be traded off through monetary values. Environmental impacts include the impacts on air, water, soil, and resource consumption eventually cause economic and social impacts too [45]. Also, qualitative analysis through expert opinion surveys on impact assessment cannot be used as a logical method for decision making due to two reasons. First, the expert opinion can be limited to a specific technology polarization on single strategy and can lack unforeseeable multidisciplinary impacts within the scope of waste management. Second, a qualitative assessment makes it difficult to compare the impacts at different stages due to the ambiguous interpretation of the magnitude and significance of impacts [46, 47]. A quantified waste management model focused upon minimizing environmental impacts, maximizing material and energy recovery, and reducing the societal costs associated with all the steps of MSW management [44]. Also, quantifiable impacts are generalizable, replicable, and easy to assist in planning decisions in the waste management sector.

### LCA Application in Waste Management

LCA is a tool to assess the environmental impacts from the cradle to the grave of a product or service [18, 25, 48]. Simplicity in the interpretation, comparability, and generalization is a key strength in this approach [49]. According to Karmpetis et al. [49], the LCA framework provided long-term environmental benefits compared with other tool options in the field. So, LCA is a commonly used assessment method to support SWM decisions. Menikpura et al. [5, 6] assessed LCA based framework by using ecosystem damage and resource depletion to evaluate environmental impacts. Lutz et al. [50] considered impacts on well-being of the community and health indicators to assess social

sustainability while Sudhir et al. [51] addressed impacts on urban poor to evaluate the sustainability of waste management strategy.

The purpose of LCA application and clear identification of the scope of the waste management process are vital in completing a successful impact assessment. The LCA framework has four sequential steps in its application. The key steps in LCA application include (1) definition of system boundary, goals, and scope, (2) inventory of life cycle activities, (3) assessment of impacts in each category, and (4) interpretation of the results [22, 52]. The goal set as to evaluate the (emission-based) environmental impacts of existing waste management strategy and proposed strategies using the impact caused by the management of 1 ton of MSW as the functional unit. One local authority boundary was used as the system boundary with the scope of cradle (waste generation point) to grave (final disposal event) of MSW within the administrative area. Emission-based impacts from transportation, recycling, anaerobic digestion, composting, sanitary landfilling, incineration, open dumping, and open burning stages of waste were used in the inventory analysis while available, verified, and reliable data were used to calculate the emission levels at each stage of waste life cycle.

Environmental impacts of waste management strategies can range from global climate change to resource depletion and pollution [24, 33]. Green House Gas (GHG) emissions from each stage are considered in this study as the proxy to assess the environmental impacts due to the availability of reliable data, relevant to study objectives, and generalizability of impacts between different steps of waste life cycle. Life Cycle Inventory (LCI) listed out the indicators in each of the waste management stages, namely, collection and transportation, processing, and final disposal. The system boundary used as the monthly collection quantity of domestic waste by the local authority and functional unit was taken as “kilograms of GHG emissions per ton of processed MSW.” Global climate change was considered the key indicator for the assessment considering vital GHG emissions, namely, Carbon Dioxide (CO<sub>2</sub>), Methane (CH<sub>4</sub>), Short-Lived Climate Pollutants (SLCP) in the form of Black Carbon (BC), and Nitrous Oxide (N<sub>2</sub>O). Global Warming Potential (GWP) of GHG and SLCP was used with CO<sub>2</sub> equivalent emissions as the baseline. According to IPCC [53], GWP for 100 years was considered for calculations with CH<sub>4</sub> (biogenic) as 28 times, N<sub>2</sub>O as 265 times, black carbon as 590 times more potent than the emission of one unit of CO<sub>2</sub>. In each stage, positive GHG emissions were considered a negative impact on the environment while negative values contributing to emission savings were considered a positive for the environment.

### **Emission Quantification Tool (EQT)**

Emission Quantification Tool (EQT) is a rapid assessment model to quantify GHG emissions in the form of GHGs and SLCPs (BC). The tool was first developed in 2011 and updated in 2018 by the Institute for Global Environmental Strategies (IGES) on behalf of the Climate and Clean Air Coalition’s Municipal Solid Waste Initiative. The data on waste quantity, energy consumption, and fuel consumption were used in the model with an optional standardized dataset for each country or city. Simplicity of interface, adaptability to conditions, responsiveness to data gaps, and graphical interpretation of outputs were key advantages of EQT for adopting this study. Moreover, the EQT model is a useful tool for policymakers and practitioners in the waste management sector to make decisions more effectively using scientific indicators. For the impact assessment, primary data was collected from the formal and informal channels while standard data inputs were obtained

from reliable literature and related stakeholders. EQT model provided GWP of different steps unique to countries with different geographical contexts and development stages. According to guidelines given by IGES [54], key components of waste management process used in the study were as follows: (1) demographic and local authority information (baseline data), (2) transportation stage, (3) composting, (4) anaerobic digestion, (5) recycling, (6) incineration, (7) landfill categories, and (8) uncollected waste streams. Mechanical Biological Treatment (MBT) and “Open Burning and Landfill Fire” options were excluded from the assessment due to non-practice within the context. Per capita waste generation in kilograms and waste collection rates of local authorities were the data inputs for waste generation and collection stage. Fuel consumption per one kilometre of distance traveled by collection and transport vehicles was used as the indicator for waste transportation. For recycling, fossil fuel consumption per one ton of recycling waste was used while emissions generated by one ton of processed organic waste were used for composting. Landfills with gas collection mechanisms used fossil fuel consumption for one ton of waste proceeded at the landfill. Methane and nitrous oxide emissions per ton of waste combustion were used as the data input for incineration (waste-to-energy) plants. For the uncollected waste, black carbon emissions per ton of waste disposal (including open burning by households) were taken as indicators in the calculations [5, 6, 24]. Output from the EQT model compared with different alternative scenarios as well as measured in abstract form. The EQT model estimated GHG/SLCP emissions in different waste management scenarios and the emission savings in the form of energy or heat. The model was fed with context-specific verified data and in case of data unavailability, IPCC default values were used.

## Methods and Data

### Application of LCA for Waste Management

The circular economy concept has been explored on systems and processes where wastes, emissions, and energy leakages are minimized [55]. Therefore, techniques adopted on minimizing the final quantities and regenerate new products and processes are useful in achieving sustainability objectives. LCA application can provide the optimum technology mix for the MSW from resource efficiency perspective. Waste management has spatial and temporal variations whereas emission categories and levels can vary significantly. However, in line with the objectives of this study, the composition of MSW was used by comparing the nature of waste management, composition, and quality in the urban context. LCA provided most sustainable waste management strategy by using emission reduction, energy conversion, and resource management as proxies towards circular economy. Each proxy indicated economic, environmental, and social benefits which can be quantified in financial and utility terms to assess the level of benefits over different alternative scenarios of MSW management. However, monetary gains and losses in each strategy were beyond the scope of this study, hence not considered in the assessment. Circular economy oriented proxies were quantified in terms of CO<sub>2</sub> emissions in each scenario to support objective policy direction.

## Case Study

Dehiwala-Mount Lavinia Municipal Council (DMMC) is one of the highly urbanized local authorities in Colombo, Sri Lanka, with a population of 200,219 (2019). Existing waste generation amounts to approximately 185 tons per day, while about 83% is collected daily (154 tons) by formal channels. Composting and recycling plants are located within the local authority boundary, which amounts to 15%, and 21% of total collected waste, respectively. Current final disposal site of DMMC is the Karadiyana Landfill Site (KLS) which is located within 5 km of the local authority boundary. In addition, 1% of the waste is collected by informal collectors, while about 40% the of uncollected waste is dumped openly while the remaining is burnt within premises. For the assessment, the existing status was considered as a Business-As-Usual (BAU) scenario and four (4) future scenarios were proposed to compare and evaluate the sustainable waste management strategy for DMMC.

## Scenario Development

DMMC collects MSW under two main streams, namely, mixed waste and recyclable waste. Mixed waste includes processing of MSW, bulky waste, industrial waste, slaughterhouse waste, and sorted organic waste. Recyclables are collected by both the formal (local authority) and informal (private collectors) channels and processed at a separate location under the supervision of DMMC. A major drawback identified in the collection process was the uncollected waste proportion which is approximately 17% (31 tons/day) of total generated waste within DMMC and resulted in mismanagement. By considering the existing waste management mechanism (Fig. 1), ongoing plans by the local authority and future potentials as studied in the context were considered for developing five (existing–1, proposed–4) trajectories of integrated waste management for DMMC. For the clarity and differentiation of techniques, the waste management process was categorized into two stages. Stage 1 included the preprocessing and initial treatment of waste before undertaking stage 2 for final disposal. Accordingly, stage 2 indicated the end disposal strategy followed by the volume/weight reduction strategy such as sanitary landfills, waste-to-energy/incineration plants, and open dumps. All other technologies used in the intermediate stages of waste management were included in stage 1, which included composting, recycling, biogas/anaerobic digestion, and open burning of waste. Transportation of solid waste from the generation point to the end disposal site was calculated at each step and added separately as an important emission category. Additional reason for separate addition for transportation was to understand its effects as previous studies have not considered on it as a vital component in local context. Technologies used in each stage and their application are explained in Table 1.

Scenarios for integrated waste management in DMMC were developed based on two criteria: First, optimum scenarios that can be accommodated by current and ongoing projects within the local authority. Scenarios one (1) and two (2) were developed based on the expert opinion surveys and consultation of local authority personnel. Second option considered a strict focus on end disposal based on proposed two management plans namely: waste incineration and engineered sanitary landfill. Scenarios three (3) and four (4) were developed based on the maximum input for incineration and landfill projects which are in the implementation phase. Spatial distribution of MSW strategy is considered to understand the impacts of each scenario. All the strategies under stage 1 are located within the local authority boundary. A new engineered sanitary landfill is proposed at Aruwakkalu



**Table 1** Key steps involved in waste processing including its application

Type of activity	Stage 1	Stage 2	Transportation
Existing scenario	<ul style="list-style-type: none"> <li>● Composting</li> <li>● Recycling</li> <li>● Burning/throw uncollected waste</li> </ul>	<ul style="list-style-type: none"> <li>● Sanitary landfill</li> <li>● Open dump</li> </ul>	<ul style="list-style-type: none"> <li>● Old trucks</li> <li>● Tractors</li> </ul>
Proposed scenarios	<ul style="list-style-type: none"> <li>● Composting</li> <li>● Recycling</li> <li>● Anaerobic digestion</li> </ul>	<ul style="list-style-type: none"> <li>● Incineration</li> <li>● Sanitary landfill</li> </ul>	<ul style="list-style-type: none"> <li>● Old trucks</li> <li>● Modern trucks</li> <li>● Rail</li> </ul>

Derived from EQT model according to the existing and proposed scenarios

(ASL) by the government, about 200 km away from Colombo. ASL was proposed due to land scarcity, disaster risks, and public opposition for increasing waste dumping sites in city centers. DMMC has considered this option to manage the rising waste generation and management deficiencies in existing disposal sites. MSW is proposed to collect at a central transfer station and then transport to the landfill using the railway network [31]. Average distance from the source to the transfer station by road was about 30 km, while the distance to the final disposal site (ASL) was about 180 km from the transfer station by rail. Considering transportation options, ASL has the highest distance for waste management life cycle, which is the first of such cases in Sri Lanka. Therefore, it is necessary to understand the impacts in the context of all available options. In this study, long-distance transportation of waste is considered a vital component in the path towards a circular economy hence used in scenario 4. Total waste composition is divided among four scenarios based on the priority of each technology. Scenario 1 considered the optimization of BAU scenario, while scenario 2 included the incineration and landfill components together to evaluate the impacts of both technologies. Scenario 3 considered complete incineration of mixed waste, while scenario 4 used no waste in the incineration process. Composting and AD were not prioritized in scenarios 3 and 4 due to the maximization of potentials of incineration and sanitary landfills, operational constraints, and land scarcity reasons in city scale. The waste composition used for the analysis is shown in Table 2.

**Table 2** Composition of waste in each scenario

Utilization of MSW	Waste Composition in each scenario (percentage)				
	BAU	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Composting	15%	16%	16%	0	5%
Anaerobic digestion (AD)	0	7%	6%	0	0
Recycling	22%	24%	25%	25%	27%
Incineration	0	0	27%	67%	0
Sanitary landfill	47%	43%	21%	8%	68%
Uncollected waste	16%	10%	5%	0	0
Total collected quantity (in tons)	<b>154</b>	<b>166</b>	<b>175</b>	<b>185</b>	<b>185</b>
Total uncollected quantity (in tons)	<b>31</b>	<b>19</b>	<b>10</b>	-	-

Prepared by the author based on expert opinion survey

The waste composition was decided through the inputs from a panel of experts from the industry. The experts ranged from the public and private sector engaged in waste management, and existing landfill operators, to non-governmental agencies engaged in waste-related impacts and community projects. The scenario comparison targeted four key questions raised by the expert opinion survey such as the following:

- Can the local authorities manage the impacts through optimization of existing resources instead of focusing on new technologies? (Scenario 1)
- Will the proportional quantities of waste managed by incineration and transport to a distant landfill (ASL) support positive impacts in the management? (Scenario 2)
- Can incineration of waste solve the rising waste quantities related problems and justify the need for the technology? (Scenario 3)
- Can the distant landfill (ASL) help manage the land scarcity problem in Colombo and its suburbs? (Scenario 4)

The representative sample of experts included the Central Environmental Authority (regulator of environmental management), DMMC (vested power to manage the waste within the local authority boundary), Urban Development Authority (urban planning and management agency), Sevanatha, and Janathakshan (non-governmental agencies actively involved in waste management). The experts were interviewed separately for scenario development and the Delphi method was followed for deductive reasoning and finalization of results.

## Impact Calculations

Transportation involved the movement of MSW from source to transfer stations and the processed waste into final disposal. For incineration, transportation of fly ash from the incineration plant to the landfill site is added (Fig. 1). Emissions from trucks, tractors, compactors, and railways were used in the assessment. In composting, GHGs and SLCPs are the potential emissions from operational activities and organic waste degradation processes. Furthermore, the degradable organic carbon in the waste material is converted into  $\text{CO}_2$  and produces  $\text{CH}_4$  and  $\text{N}_2\text{O}$  in minor concentrations. However, manufactured compost can replace the chemical fertilizer thereby reducing the emissions in agriculture. The savings were calculated as the avoided emissions and resulted as negative values. In the anaerobic digestion process, grid electricity consumption in operation (GHGs and BC) and leakage from the reactor (GHGs) are two main ways of emissions. Avoiding GHG emissions by utilizing digestives and replacement of chemical fertilizer was calculated as the same as composting. Material recovery in the recycling process saved emissions significantly where avoided GHG/SLCP were used as negative values in the calculations. Incineration plants are efficient and sustainable for land-scarce cities due to the reduction of MSW volume and weight in a short period of time. Net GHG emissions from incineration are the emissions from operation and combustion. Moreover, incineration generates energy and heat as savings of emissions from the operation. Sanitary landfills pose comparatively fewer impacts than open dumping sites and cost-effective solutions for developing countries. Methane correction factor and oxidation factor have different values from one to another and standard factors were used for South Asia in the EQT calculations. Methane recovery in the sanitary landfills is used as a saving for the overall emission baseline. Due to collection deficiencies within DMMC, open burning and illegal dumping were considered in BAU,

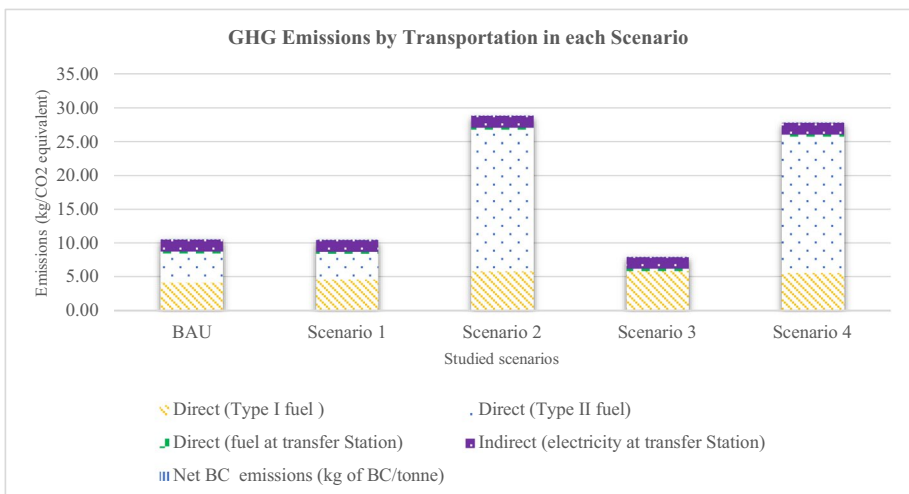
scenarios 1, and 2 of the waste life cycle. Fossil fuel-based CO<sub>2</sub> emissions, CH<sub>4</sub> emissions, and other gaseous emissions were considered in open burning and dumping processes.

## Results and Discussion

Scenario analysis was completed by using the waste management data from DMMC and existing waste processing centers within the local authority limits. Information of ongoing and proposed waste management projects were obtained from respective project officers and default values of EQT model were used for the standard data and in unavailable circumstances. Comparison results were then validated by the expert group to seek answers to the raised questions in the data collection stage.

### Emissions in the Transportation of MSW

Total emissions from each scenario are shown in Fig. 2 proved the impact of MSW transportation. Absolute values for total emissions for BAU scenario, scenarios 1, 2, 3, and 4 were 10.61, 10.56, 29.20, 7.99, and 28.16 kg of CO<sub>2</sub>-eq/ton respectively. Overall, incineration of total waste within the local authority (scenario 3) has resulted in the lowest emissions while scenarios 2 and 4 recorded the highest levels of emissions, approximately threefold higher than the BAU scenario. As expected, scenarios 2 and 4 had three times higher fuel-based emissions than BAU scenario due to the 210-km-long journey to ASL. Type I fuel category considered the waste collected from generation point to transfer station and type II fuel category was considered for waste delivered to end disposal site. The proportion of emissions in the transportation (type II category) of waste to ASL was 71.7% in scenario 2 while it was 71.5% in scenario 4. Moreover, long-term implications of such transportation could increase the emissions exponentially due to the nature of operations and vulnerability of the process. In addition, scenario 2 used 40 tons of waste transported



**Fig. 2** Total emissions in kg of CO<sub>2</sub>-eq/ton resulted from each scenario studied

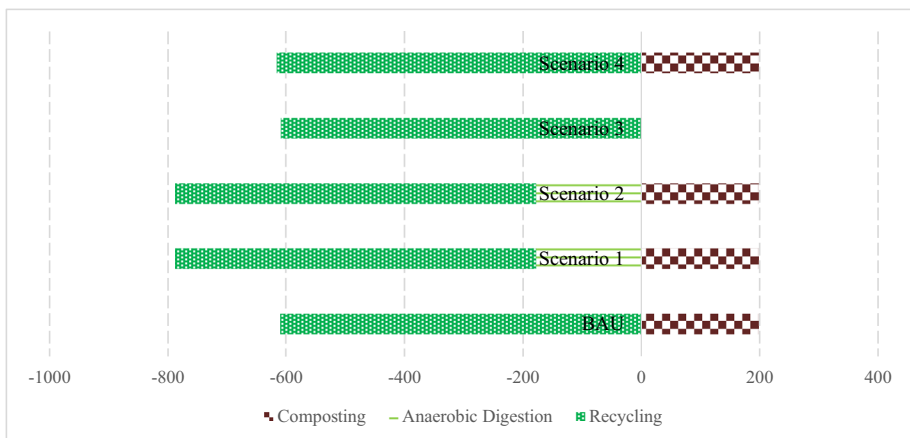
to ASL while scenario 4 considered 127 tons which resulted in similar amounts of emissions. Therefore, regardless of the quantity of waste, long-distance transportation has a significant impact on the environment. Also, optimization of existing resources in scenario 1 did not improve the emissions compared with BAU. In each scenario, the emissions generated by the type I category had a similar outcome due to similar distance traveled in the collection of MSW from households to the transfer station.

### Stage 1 Strategies: Recycling, Composting, and Anaerobic Digestion

Composting and Anaerobic Digestion (AD) were used as interim strategies to treat organic waste within the local authority. Figure 3 shows the emission levels in each scenario. In DMMC, AD was not practiced in the BAU scenario due to land scarcity, operational costs, and mixed nature of waste. However, AD shows a significant positive impact on the environment due to the recovery of methane during the process. Overall, AD generated negative emissions due to (1) production of methane as a fuel source to replace coal, and (2) compost as a byproduct to replace chemical fertilizer. However, due to implementation limitations of AD, scenarios 1 and 2 used about 5–7% of total waste input for the assessment. AD needs trained staff, dedicated maintenance, and frequent monitoring which caused limited use in the current practice. However, AD reduces the volume of waste and supports the energy demand which proved to be vital for circular economy objectives too.

Composting is also a land-demanding method with no recovery of CO<sub>2</sub> during the process. BAU, scenario 1, and 2 considered approximately 30 tons and scenario 4 used 10 tons of MSW per day for composting. However, the CO<sub>2</sub> generation from each option generated about 200 kg (CO<sub>2</sub> eq./ton) of emissions. This revealed that the composting process has negative impacts on the environment with only about 11% of efficiency in producing fertilizer from 1 ton of waste input. According to expert opinions, composting is a declining strategy in DMMC and Sri Lankan context showing negative impacts from the environmental perspective as well.

BAU scenario used about 38 tons of recyclables and the maximum reached as 45 tons per day with improvements in the collection mechanism and regulatory framework as identified in the expert opinion survey. A total of 25% of total waste produced in DMMC



**Fig. 3** Total emissions and savings from composting, anaerobic digestion, and recycling in each scenario

used for recycling where assessment revealed the CO<sub>2</sub> emissions savings were over 600 kg (CO<sub>2</sub> eq./ton) from each scenario. GHG savings included CH<sub>4</sub>, CO<sub>2</sub>, N<sub>2</sub>O, and BC avoided through material recovery, which surpassed the fuel consumption-based emissions in the process approximately 2 times. Therefore, recycling proved to be an environmentally friendly strategy in the waste life cycle in DMMC. Total emissions and savings in each scenario are shown in Fig. 3 and detailed emission categories in each scenario under stage 1 are illustrated in annexure 1.

BAU, scenarios 1, and 2 had uncollected waste quantities of 31, 19, and 9 tons respectively. According to Census records [56], 63% of uncollected waste was openly burnt while 37% was dumped by the residents in DMMC. While the ratio of burning and open dumping was hard to assess in practice, 1:1 ratio of burning and open dumping was considered in scenarios 1 and 2 (GHG emissions at each stage are illustrated in the annexure 1). In comparison, the highest emissions were recorded in scenarios 1 and 2 where waste burn to waste dump ratio used as 50% each. However, emissions from uncollected waste were eliminated in scenarios 3 and 4 assuming no uncollected waste within DMMC.

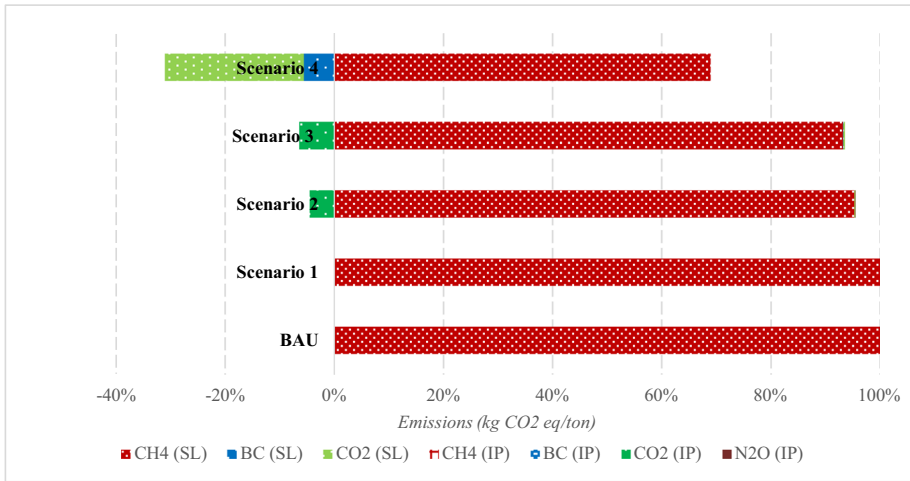
## Stage 2 Strategies: Incineration and Sanitary Landfill

Incineration of mixed waste was considered in scenarios 2 and 3 with 50 and 125 tons of MSW per day respectively. MSW quantities for scenario 2 were given by expert surveys while scenario 3 used total produced mixed waste within DMMC by excluding recyclables only. Diesel fuel-operated continuous stoker-type incineration plant was considered to evaluate environmental impacts. With the electricity recovery option, incineration has saved about 50 kg (CO<sub>2</sub> eq./ton) of emissions in the process. However, incineration plants are operated with higher quantities of waste than generated in this study which is expected to have better positive environmental impacts. The electricity and heat recovery has had a significant positive environmental impact on avoiding coal-based GHG emissions in the process.

Landfilling is a necessary end disposal method regardless of the pretreatment method used. BAU scenario used 88 tons of mixed waste into landfill while scenarios 1, 2, 3, and 4 used approximately 81, 40, 15, and 127 tons per day respectively. In addition, scenarios 2 and 4 considered ASL as the end disposal site (210 km away from the generated site) while BAU, scenario 1, and 3 used the existing landfill at Karadiyana (KLS) within waste generated locality. KLS is a converted landfill into open dump (<5 m shallow), while ASL is a semi-aerobic managed landfill with gas recovery. Net GHG emissions of BAU scenario and scenarios 1, 2, 3, and 4 produced 534.60, 529.26, 1331.59, 685.63, and 112.75 kg of emissions (CO<sub>2</sub> eq/ton) respectively. Therefore, ASL resulted in minimum emissions which is a better option than all other existing options. Out of all, scenario 2 generated the highest quantity of emissions resulting from biogenic methane emissions in the waste degradation. Methane emissions at KLS landfill caused SLCPs and CO<sub>2</sub> emissions as there was no mechanism to recover the GHGs in the process. Total GHG emissions and savings in the incineration process (IP) and sanitary landfills (SL) are illustrated in Fig. 4.

## Total Emissions in Each Scenario

Total GHG emissions considered in each scenario were added together to estimate the optimum waste management scenario within DMMC. Accordingly, Table 3 shows the net emissions in each step of the life cycle of waste.



**Fig. 4** Net GHG emissions from incineration process (IP) and sanitary landfills (SL) (kg CO<sub>2</sub> eq./ton)

**Table 3** Net emissions of life cycle of waste in identified scenarios

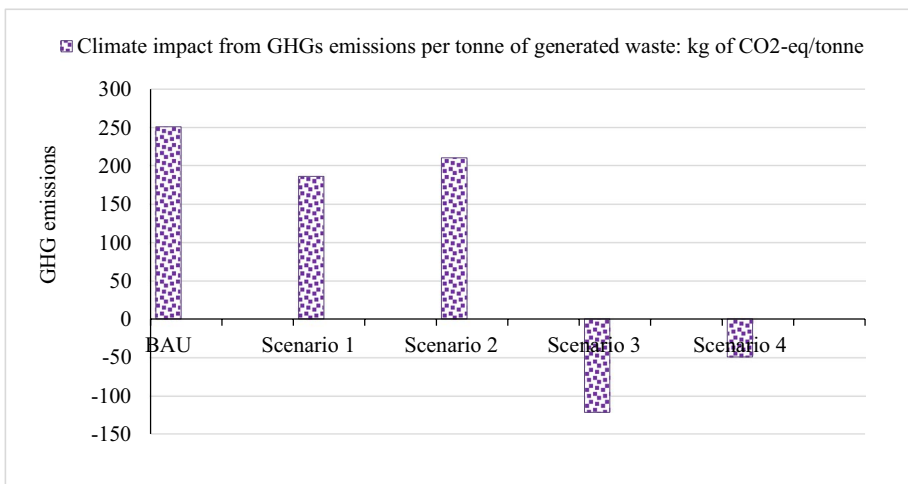
Description	GHGs/SLCPs emission per ton of generated waste				
	BAU	Scenario 1	Scenario 2	Scenario 3	Scenario 4
CH <sub>4</sub>	12.828	11.394	12.203	1.961	4.566
BC	0.067	0.033	0.103	-0.003	-0.017
CO <sub>2</sub>	-120.108	-145.489	-147.666	-176.647	-181.540
N <sub>2</sub> O	0.045	0.048	0.061	0.000	0.016
Climate impact from 1 ton of MSW	<b>250.966</b>	<b>186.238</b>	<b>210.325</b>	<b>-121.842</b>	<b>-49.380</b>

EQT model results by the author

According to Table 3, every scenario contributed positively within the MSW life cycle at DMMC compared with the BAU scenario. Scenarios 1 and 2 utilized the existing resources to optimize the waste management process as it has improved about 25% and 16% than the BAU scenario respectively. Net emissions of scenario 2 increased as compared with scenario 1 due to incineration (N<sub>2</sub>O) and transportation to ASL (CO<sub>2</sub>). The use of multiple methods for final treatment (category 2) was not a viable option for DMMC. Scenarios 3 and 4 produced positive environmental impacts which were about 150% and 120% of improvement compared with the BAU scenario. This revealed that the use of either incineration or sanitary landfill is a reliable option to consider from the environmental perspective. The use of KSL for the end disposal (scenario 3) and 210 km of transportation distance (scenario 4) caused a significant negative environmental impact, even though the net impact is positive (Table 3). Moreover, CO<sub>2</sub> emissions were negative in each scenario resulting from the recycling of up to 25% of total generated waste within DMMC. Scenario 3 provided the highest positive outcomes with proportionate waste quantities of 25% of recycling, 67% of incineration, and 8% of sanitary landfill. The results were

verified by the second round of consultation of experts to evaluate the practical implications of each process. The net emissions of each scenario are shown in Fig. 5.

Life cycle assessment (LCA) is a tool to assess the environmental impacts of municipal solid waste from cradle to grave. In most cases, waste management decisions are conducted based on financial criteria without considering the long-term environmental impacts from such decisions. Therefore, this study proposed an alternative framework to support the optimum integration of waste management strategies among urban local authorities. DMMC, one of the highly urbanized local authorities in Colombo, Sri Lanka, was selected to assess the optimum alternative of four proposed scenarios in contrast to the business-as-usual scenario. Scenario 1 used an optimized resource plan while scenarios 2, 3, and 4 used newly introduced technologies such as incineration plants and engineered sanitary landfills to evaluate the gains and costs of multiple applications. The results revealed that scenario 3, which emphasized incineration of organic waste and disposal within the local authority boundary, provided the optimum solution. Transportation of waste to a distant sanitary landfill 210 km away from the source caused significant negative environmental impacts (scenarios 2 and 4). Moreover, recycling, and anaerobic digestion provided positive environmental impacts by saving, and capturing GHG emissions respectively. Also, composting released similar amounts of emissions in each scenario while burning of waste released toxic short-lived carbon particles (black carbon) harmful to the environment and human health. The assessment results of DMMC provided key recommendations to reconsider its options available for MSW management. These recommendations include prioritizing recyclables by incorporating informal sectors for their collection and private sectors for the recycling process, withdrawing the ASL option for waste transportation as it incurs significant costs in terms of transportation and management, reassessing the importance of composting and anaerobic digestion within the local authority boundary, and eliminating the health and environmental damage by ensuring 100% collection of generated waste within the local authority boundary. The impacts of transportation, preliminary waste treatment (stage 1), and final disposal methods (stage 2) were important junctures for effective decision-making. This is an important finding for local authorities in the Sri Lankan context as



**Fig. 5** Net climate impact from selected scenarios within DMMC

priorities were given to end disposal techniques instead of optimization options. Application of the life cycle assessment framework to the waste management process improves not only scientific inputs in the decision-making process but also the input–output ratio of waste in each technology available to local authorities. Therefore, the LCA framework acts as a feasibility tool to minimize resource wastage and evaluate future growth scenarios, such as MSW growth and land management within cities.

Mean waste collection efficiency in municipal councils in Sri Lanka is approximately 50% and over 85% of waste ends up in open dumping sites or converted landfills into open dumps [57]. Moreover, an open waste dump collapsed due to exceeded loading capacity in 2016 [2]. Development of sanitary landfill (ASL) about 200 km away from the waste source was clearly an unsustainable strategy. However, these decisions make waste management a complex task with socio-economic and environmental conflicts. Therefore, LCA-based approach can simplify the waste management strategy while creating opportunities for policymakers to develop actionable strategies at the ground level. Moreover, the integration of stakeholders from local to the national level is essential to coordinate policy decisions among different socio-economic groups. Therefore, MSW management at the local authority level can convert from linear process (collection-treatment-disposal) towards circular approach (collection-treatment-renewal-reuse) by utilizing local resources. Commitment of political authorities, institutional set-up, and specified economic sectors can then be directed towards sustainable resource management especially in developing countries.

## Conclusion

This study used life cycle assessment as a tool to evaluate the potential environmental impacts of waste management process by comparing alternative waste management streams with business-as-usual scenario. Local authorities in developing countries have identified the importance of an integrated approach as well as combined socio-economic efforts to tackle the environmental and related social and health issues in recent years. A circular economy-based approach is a critical step towards sustainable waste management using resource-oriented pathways. Scientific decision-making process followed by methods like LCA assists policy makers in directing sustainable alternatives to traditional waste disposal mechanisms while generating value creation pathways. For example, recycling and incineration plants were evaluated in Sri Lanka from limited financial and scalability perspectives, which has a higher potential for solving rising waste demand while creating new sectors of employment. Similarly, improvement of transportation aspect with modern technologies and combined operations could optimize the service delivery as well as the resource efficiency. Therefore, the use of emission-based criteria would be a stepping-stone for circular economic growth while converging the conceptualization of waste management towards sustainable development goals. This is particularly important for developing countries like Sri Lanka which face rapid urbanization and induced growth of waste materials.

This study followed environmental impacts using emissions as the proxy to assess the potential of waste management options at DMMC, a local authority located in Colombo, Sri Lanka. Applying the method to multiple local authorities with context-specific features is necessary to generalize the findings. Nevertheless, the EQT model proved its flexibility and validity in calculating emission categories and served as a valuable tool for decision-making. Impact prediction tools are essential in the planning stage of waste management



strategies where cities struggle with unsafe waste disposal methods in developing countries like Sri Lanka. This study can be expanded to link the financial criteria for MSW management scenarios to evaluate the trade-off between economic costs and environmental gains in short-, medium-, and long-term aspects. Also, by integrating spatial parameters, the tool can determine the optimum location for a city's waste disposal with the required capacity of each waste management scenario. Prediction of impacts is an important step for local authorities to avoid misuse of financial and human resources through trial-and-error strategies. Therefore, LCA is a vital framework for identifying key efficiency improvements in the existing waste management practice prior to introducing new technologies within the MSW management framework.

Conflicts among economic gains and environmental benefits, waste management as an end-of-life product of consumption, and the application of financial criteria to assess waste management strategy were long stayed myths in the waste management sector. Circular economy is not something affordable and achievable by only the developed countries and also a vital component for developing countries to meet the challenges posed by rapid urbanization. This study covered circular economic policy needs in three aspects. First, to formulate an objective appraisal of waste management strategies, second, to derive performance indicators or benchmarks to support decision-makers in the waste management sector, and third, to link policy decisions with ground level applications to foresee the effects of such decisions in the planning process. LCA application can not only answer the question of “why waste management strategies fail in developing countries?” but also answers “how to integrate the waste management with development goals using holistic approach?” One of the fundamental issues addressed through this study was to evaluate the mismatch of policy directives and real ground situations in MSW strategies in developing countries like Sri Lanka. It is well noted that toothless policies and lack of target-oriented practices cause waste management a nuisance for many cities in the world. Conversion of linear economic policies towards circular economy is not a simple task; however, waste management could be the bridging sector for cities to adopt workable solutions in achieving sustainability agenda in the long run. This study is a vital piece for linking environmental benefits with socio-economic targets in cities and thereby developing an action-oriented circular economic policy. However, identification of stakeholder responsibilities, spatial and temporal implications, and clear socio-economic benefits is necessary for deriving strategies to implement the policy directives.

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**Author Contribution** OVP conceptualized the study and developed the methodology to validate the conceptualized model. LND collected the data, conducted the analysis, and documented the results. OVP assisted in writing the results and validation of the results with data. LND finalized the analysis section. All authors, read, edited, and approved the final manuscript.

**Data Availability** Yes, authors can provide the supporting data if required.

## Declarations

**Conflict of Interest** The authors declare no competing interests.

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