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Research article

Environmental and economic performances of municipal solid waste management strategies based on LCA method: A case study of kinshasa

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ABSTRACT

Like many populated urban agglomerations in Africa, Kinshasa, the capital of Democratic Republic of Congo, faces several challenges to manage its exponentially growing Municipal Solid Waste. With its 12, 000, 000 people daily generating 7800 tons of Municipal Solid waste, the city still struggles with basic services such as waste collection and sanitary landfill. This causes major social, environmental and health related issues. With the aim of contributing to the implementation of a better management system in Kinshasa, this study evaluates the environmental impact and the cost of the existing waste management framework and proposes 6 alternative scenarios. Each scenario attempts to optimize Greenhouse gas emissions and cost, using the Life Cycle Assessment approach. Results show that the current municipal solid waste management in Kinshasa city emits 640,673 tons of CO_2 equivalent per year and costs a total of 17, 776, 169.78USD yearly. Focusing on increasing waste collection coverage and recycling activities in the proposed 6 scenarios, scenario 4 where all municipal solid waste is collected, produces 4,042,402 tons of CO_2 equivalent per year and costs 143, 296, 983.4 yearly. In scenario 7, considered the most optimized management model for Kinshasa in this study, municipal solid waste is valorized through different treatment processes and atmospheric pollution reaches 2,835,491 tons of CO_2 equivalent yearly, with a management cost of 152, 790, 779.4 USD/year. This study finds that the optimization of the Municipal Solid Waste management system in Kinshasa city causes the atmospheric pollution in terms of CO_2 equivalent to decrease by half, when all waste is collected. Landfill diversion rate reaches up to 70%, but the overall MSW management cost increases by almost eight times as much as the current operational cost. The optimization of the management system is done by increasing waste collection coverage and implementing diverse streams of waste valorization. Despite the wide use of the Life Cycle Assessment method in waste management and decision making, this method has not yet been, to the best knowledge of the authors, applied in estimating Greenhouse gas emissions and cost of the Municipal Solid Waste in the specific context of Kinshasa city.

1. Introduction

In Africa, only 55% of the annually generated 125 million tons of municipal solid waste (MSW) is collected [1]. This amount

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reduces further to 44% in sub-Saharan Africa [2]. It is not uncommon to observe small and large dumping sites nearby habitations across the African continent [3]. Over 90% of the produced waste is disposed of in open dumpsites and uncontrolled landfills [4], and 19 of the world's 50 biggest dumping sites are located in this region [4]. Population growth is one of the major drivers for waste generation increase [5]. Compared to other urban agglomerations, the population in African cities has been growing rapidly in recent years, with a 150% increase between 2000 and 2015 [6] and the trend is projected to nearly double by 2050 [7]. This situation calls for implementing adequate MSW management systems to tackle numerous public health concerns and the increasing negative environmental impacts [4].

Proximity to waste sites increases the occurrence of diseases such as malaria, typhoid, cholera, dengue, yellow fever, gastroenteritis, and hepatitis [8,9] due to created environmental conditions ideal for the breeding of mosquitoes, flies, and gastrointestinal pathogens [10]. In Africa, 23% of Vector-borne, diarrheal, and cardiovascular diseases are attributed to environmental factors [11]. The current poor MSW management systems on the African continent are worsening the effects of natural disasters such as flooding and inundation [4,12] and causing extensive environmental pollution across air, soil and water bodies [1,4,13,14]. Because 58% of waste produced in Africa is organic, its degradation has a non-negligible contribution to global warming [15]. In fact, the IPCC estimates that methane from solid waste in landfill sites contributed 3% to global greenhouse gas (GHG) emissions in 2010 [16]. Improper solid waste management negatively impacts the soil by reducing its fertility due to increase of pH, salinity and alkalinity. Plastic waste prevents germination of seeds, and affects the growth of plants, which can lead to erosions [17]. In many countries, the contamination of surface water and groundwater bodies have caused negative impacts on human health and on aquatic beings due to their proximity with improperly managed landfills [18–21].

The weak MSW management system also affects the economy and social life, as it is proven that living in a filthy environment can lead to a lack of motivation and a demoralized mindset. Additionally, a visibly untidy environment promotes more crimes and other antisocial behavior, per the broken window theory [4,9,10]. Considering these multi-sectoral issues linked to MSW in Africa, most national governments have shown a need for action interest reflected in the increasing demand for international funds in the waste management sector [22]. Many African countries have undertaken actions enhancing their solid waste management systems: Kenya has increased waste recycling by 90% thanks to a project with Taka, a private company that has helped enable affordable waste collection, sorting, composting, plastic recycling, and waste purchasing in poor areas of the country. South Africa on the other hand, leverages new technologies such as smartphone applications to facilitate waste collection services [23]. A more collective effort on the continent is shown by the recent creation of the African Clean Cities Platform (ACCP) in 2017, by representatives from 24 African countries with the Ministry of Environment of Japan, the Japan International Cooperation Agency (JICA), the City of Yokohama, the United Nations Environment Programme (UNEP) and the United Nations Human Settlements Programme (UN-Habitat), with the mission to realize clean and healthy cities and achieve the Sustainable development Goals (SDGs) on waste management. Waste management in some European and American countries became more organized in administration and techniques, followed by related policies and investment in infrastructure after the industrial revolution [24]. On the other hand, African countries still face numerous challenges to overcome the present MSW chaos despite the urgent need for improvement expressed by many local governments. Most of these issues revolve around low budget allocation to the MSW sector, lack of environmental legislation and awareness [2], and other

Table 1
Kinshasa communes' demographic data [32].

#	Category	Commune name	Population (2017)	Population (2030)	Population (2040)	Area (Km^2)
1	Residential Area	[a]Gombe	80,696	124,628	149,555	29.3
2		Limete	466,113	580,315	686,868	67.6
3		Ngaliema	1,147,924	1,935,408	2,137,894	224.3
4	Old City	[a]Kintambo	179,581	179,581	179,581	2.7
5		[a]Barumbu	172,449	196,263	196,263	4.7
6		[a]Kinshasa	152,778	152,778	152,778	2.9
7		[a]Lingwala	148,534	148,534	148,534	2.9
8	New City	[a]Ngiri-ngiri	167,019	167,019	167,019	3.4
9		[a]Kasa-vubu	114,152	114,152	114,152	5
10	Planned City	[a]Kalamu	287,045	287,045	287,045	6.6
11		Lemba	505,836	742,838	742,838	23.7
12		Matete	343,584	343,584	343,584	4.9
13		[a]Bandalungwa	362,766	362,766	362,766	6.8
14		N'djili	651,007	651,007	651,007	11.4
15	Southern Suburbs	Ngaba	279,329	245,117	221,680	4
16		Selembao	471,504	536,615	592,757	23.2
17		Bumbu	536,018	470,367	425,392	5.3
18		Makala	329,725	329,725	329,725	5.6
19	Urban Periphery	Kisenso	579,147	579,147	579,147	16.6
20		Masina	1,070,858	1,070,858	1,070,858	69.7
21		Kimbanseke	1,678,395	2,974,445	2,974,445	237.8
22		Mont-ngafula	714,074	2,277,776	4,021,663	358.9
23		N'sele	772,027	2,665,247	5,242,945	898.8
24		Maluku	1,294,439	2,864,783	4,221,505	7948
Total		–	**12,505,000**	**19,999,998**	**26,000,001**	**9964.1**

[a] Communes under PARAU project.

technical aspects associated with waste collection, transportation, and storage [3]. To implement an adequate MSW management system, African countries, like other developing countries, must consider social and political implications, economic and population growth, international influence, as well as unplanned urbanization [22,25].

The Democratic Republic of Congo (DRC) is one of Africa's top countries with a rapidly increasing population. With the current population of 108, 407, 721 people [26], having increased by ~1.57 fold from 69.4 million in 2014 [26,27], the DRC's MSW management sector faces multiple challenges due to the increasing amount of waste generated. In 2010 alone, the country produced an estimated 4.55 million tons of MSW, mostly in urban cities [28]. In 2012, the daily waste generation rate was estimated at 0.50 kg per capita, with an expected increase of ~0.75 kg by 2025 [28].

Kinshasa, the capital of the Democratic Republic of Congo, is the 30th world's largest city and the third largest city in Africa [29]. It is divided into 24 communes. Its urban agglomeration covers 9965 km^2 [30], of which only 11% (1100 km^2) is occupied [31]. The city has an average of 6 people per household and an estimated population of 12, 505, 000 in 2017 [29,32]. Based on a 5.5% growth rate estimation by the Institut National de la Statistique (INS), the population of Kinshasa should have increased to 15, 960, 000 in 2021 [33] and is expected to reach 26 million by 2040 (Table 1).

This rapidly growing city generates about 0.5 kg/capita per day with a projection of 0.7 kg increase by 2025 [6]. The total MSW generated is 7800 tons per day [22,34]; however, only 14% is collected and disposed of in a landfill. The efficiency of the MSW management system often indicates the performance level of the city's governance [3,35]. Kinshasa is one of the dirtiest cities in Africa, often described in publications as an example of a weak and highly neglected MSW system [6]. Historically, the implementation of MSW management in Kinshasa has been gradual. But due to a rapid population increase since the country's independence in 1960, a fast and unplanned urbanization and decades long of socio-economic and political instability, the city only saw the birth of a concrete executive MSW management plan in 2010 [31,36,37]. This was with the start of Projet d'Appui et de Réhabilitation des infrastructures routières en RDC et d'Amélioration de l'assainissement Urbain de Kinshasa (PARAU) project, supported by the European Union [6]. The PARAU project was implemented in only nine communes (Table 1) under the governmental technical organ in charge of waste management called "Régie d'Assainissement de Kinshasa (RASKIN)" that was created 2 years prior and allowed for the creation of 61 transfer stations as well as the first sanitary landfill located about 35 km away from the city center.

In addition to RASKIN, approximately 60 NGOs oversee the cleaning of major roads in 5 communes with funding from the Bureau Centrale de Coordination (BCECO), an agency related to the Ministry of Finance [6,36]. PARAU had a monthly operational cost of 1, 400,000 €, after its completion in 2015, the city could only sustain less than half the usual operational cost. This occasioned a breakage of material and equipment, a slower collection rhythm and the destruction of some transfer stations by the population from the nuisances created by waste accumulation [38]. By 2018, only 21 waste transfer stations were in operation, and the sanitary landfill looked more and more like a simple dumpsite. The city reported to the ACCP that MSW composition in Kinshasa is dominated by organic waste, followed by plastics (figure 1) [6]. These estimations are similar to the MSW composition in sub-Saharan countries (figure 2) and developing countries (figure 3), as respectively estimated by the UNEP by the World Bank [4,34].

Amongst other major issues inhibiting the implementation of an adequate MSW system in Kinshasa, such as lack of clear work repartition and responsibility, lack of adaptive planning, lack of public awareness regarding environmental issues, lack of Public Private Partnership and financial constraints, the lack of clear laws and policy is often cited [39]. For the MSW management's legal sector, the city can only rely on basic environmental protection-related laws from the country's 2016 constitution (Law N°11/009 of July 9th, 2011, related to fundamental principles relating to the protection of the environment) [40], which is often found to be too general and incomplete to be efficiently applied.

The UN recommends, amongst many other suggestions, that the effort to an integrated MSW management system focuses on increasing collection coverage and material recycling rate, controlling landfill sites, and improving data availability for evidence-based decision-making and solution implementation [4,16]. The ACCP states that in the case of African countries, it is crucial to work toward understanding each country's situation to successfully formulate and implement an adequate management plan [10].

The city of Kinshasa has demonstrated efforts to ameliorate the current MSW situation by creating waste management campaigns such as "*Kin bopeto*" [41], while also getting involved in international platforms on MSW such as ACCP. The booming of private

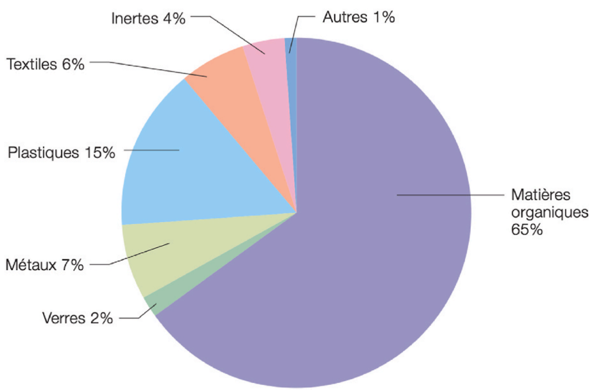

Figure 1. MSW composition in Kinshasa city [6] (Autres=others, métaux=metal, Verres=glass, Matières organiques=organic matter)

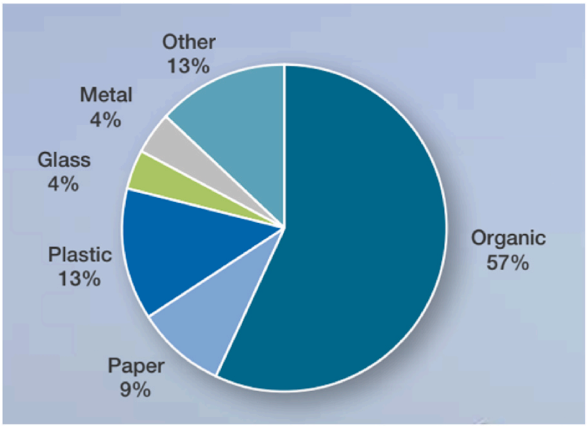

Figure 2. MSW in sub-Saharan Africa [4]

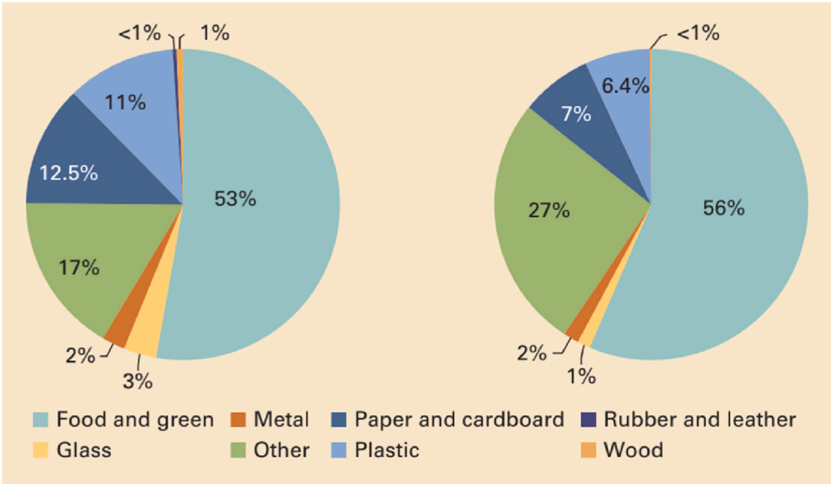

Figure 3. MSW composition in low-middle income countries (on the left) and in low-income countries (on the right) [34]

enterprises in the recycling business is also an indication of the current MSW crisis and the undertaking of pragmatic actions towards the enhancement of MSW management system [42].

In these regards, this study subscribes to the effort of providing researchers and decision makers of the city, with basic data to orientate further research and policies elaboration.

Using the Life Cycle Assessment methodology as an analysis tool, the objectives of this study are as follows.

- Evaluate the cost and the environmental impact of the MSW management currently implemented in Kinshasa;
- Propose six other MSW scenarios with optimized costs and environmental impacts, based on national and international goals.

The research focuses on comparing parameters for each scenario, parameters such as management cost, GHG emissions, water pollution, fuel consumption and landfill diversion. The study results can support decision makers to elaborate the MSW management framework and policies that focus on reducing the environmental impact of MSW in Kinshasa.

Although it is widely accepted that the effectiveness of LCA application in decision making is significant for both developed and developing countries' MSW management, no LCA has been previously conducted, to the best knowledge of the authors, in the specific context of the Democratic Republic of the Congo. Furthermore, this study is the first LCA analysis in Kinshasa city, focusing on Greenhouse Gas emissions and cost of MSW management.

2. Materials and methods

2.1. Management options description

2.1.1. Life Cycle Assessment

Life cycle assessment (LCA) is an input-output method to determine the environmental impact of materials creation usage and end of life. It can be applied to a product, such as a plastic bottle or a service, such as waste management [30]. LCA can be done throughout different life phases of a product or service via concepts such as cradle to cradle, cradle to grave, and gate to grave based on the scope of the assessment. Waste management exists in the technical framework of LCA [44]. In this case, it considers when the material ceases to have value and becomes waste, to when waste becomes inert landfill material or is converted to air and/or water emissions [45].

Using LCA, it has been determined that landfill mitigation strategies such as recycling and other methods of waste management improvement can reduce up to 15% of global GHG emissions [16], hereby positively impacting the public health sector. Several studies have demonstrated that applying LCA thinking in the waste management sector helps in identifying the most environmentally and economically efficient array of treatment processes, in order to choose the one that fits best in specific geographical contexts. LCA has been widely used in the process of selecting optimized Municipal Solid Waste management frameworks in developing countries such as India [46,47], in rich developing countries such as China [48,49] as well as in developed countries such as Germany [50], Sweden [51], United Kingdom [52], Singapore [53] and the United States of America [54]. In Nottingham (England), for example, results from LCA indicated an improvement in greenhouse gas reduction while improving waste collection, treatment, and material recycling [55]. Furthermore, in Arusha (Tanzania), LCA results revealed that a combination of recycling, composting, and landfill performed better in alleviating environmental impacts [56]. This underlines the importance of conducting such studies in the waste management sector to induce evidence-based decision-making and efficiently contribute to improving the MSW field.

It is important to mention that only 199 LCA articles in Africa currently exist despite the several benefits of applying LCA in solid waste management. These benefits include evaluation of environmental burdens, analysis of system performance and ability to compare several alternatives with possibility of improvement [57]. There is also worth noting LCA's popular application in multiple disciplines to evaluate resource management from the perspectives of specific products, processes, and services [58]. This number of LCA articles is relatively small compared to other non-African developing countries. Moreover, no LCA studies have been conducted in the waste management sector or any other sector in D.R.C despite the rapid population growth implying an increase in waste production [59].

As a methodology, conducting LCA must follow guidelines by ISO 14040 under the following steps: Goal and scope, life cycle inventory, impact assessment and Interpretation. The first two steps set all the necessary inputs to commence the assessment, the third step defines and quantifies the impact based on chosen inputs and the last step explains obtained numbers (outputs). Furthermore, interpreted results can be applied in strategy planning, product development, public policy planning, among others [60].

Application of LCA on MSW is usually conducted with the help of software, amongst which, Integrated Waste Management Model (IWM-2) that is used in this study. IWM-2 has some limitations such as it only evaluates emissions in two ecosystem compartments: air and water but not in soils. It is known to identify a smaller number of substances emitted compared to generic software. Also, it is not possible to choose various types of Life Cycle Impact Assessment (LCIA) approaches within IWM-2, which makes it hard to conduct a sensitivity analysis. Moreover, IWM-2 does not consider resource consumption, nor does it directly measure major impact factors such as acidification potential (even though it measures the main acidifying contaminants SO_2, NOx and NHx), nor human toxicity in 1,4-DB equivalent [61]. It is also important to note that IWM-2 does not evaluate the impact of uncollected waste, meaning the impact scope remains within the quantity of MSW collected and not the overall waste produced.

Nonetheless, IWM-2 has the advantage to evaluate existing and new models of waste management systems using an integrated database. It also has the advantage of conducting an LCA focused on waste management systems rather than conducting a general impact assessment, using programs like SimaPro, team or Gabi. IWM-2 was developed for only waste management purposes, and is highly sensitive to waste composition, as it considers the environmental impact resulting from reaction between different components in waste composition [61].

2.1.2. Scope

LCA can be broad depending on the material or service to be assessed. The broader it is, the less precise the application for integrated management will be, especially because each city has a unique history, socio-economic conditions, and culture that highly influence solid waste management planning and implementation [22]. Apart from defining the quantity of MSW to be assessed, it is necessary to locate in time and space the object to be assessed. In this case study, our goal is to define the environmental impact in terms of CO_2 equivalent, of the current MSW management implemented in Kinshasa city and to assess the environmental impacts of different waste management models designed based on national and international goals for the MSW management sector. Thus, the aspects considered in this LCA are.

a. Functional unit defined as the unit mass of MSW (tons) generated in Kinshasa city
b. System boundaries based on the impact of MSW management using a cradle-to-grave approach as defined by Forbes R [45]. The study compares seven scenarios, each of them taking the previous one as a baseline. For all scenarios, MSW composition remains the same as the one shown in Fig. 1, the collection type is curbside, and 50% of leachate produced at the landfill is collected. The primary factor for SWM in most large cities of developing countries is public health; thus, decision-makers set up systems for moving waste away from habitations first and explore other options such as recycling and other types of waste valorization later

Table 2
MSW scenarios description.

Scenarios	Collection	Sorting	Recycling	Composting	Incineration	Biogaz	Landfill operations				
							waste reception	Gas collection	Energy recovery	Leachate collection	Leachate treatment efficiency
1	14%	0	0%	0	0	0	100%	0	0	50%	0
2	57%	0	4%	0	0	0	96%	0	0	50%	0
3	88%	10%	10%	2%	0	0	88%	10%	10%	50%	10%
4	100%	20%	20%	4%	0	0	76%	20%	20%	50%	20%
5	100%	30%	30%	6%	2%	0	62%	30%	30%	50%	30%
6	100%	40%	40%	8%	4%	2%	46%	40%	40%	50%	40%
7	100%	50%	50%	10%	6%	4%	30%	50%	50%	50%	50%

[22]. The top priorities for integrated MSW management in African countries are eliminating open dumping sites and increasing waste collection coverage [4]. Therefore, scenarios 2 to 4 focus on gradually increasing MSW collection rate, starting with the most densely populated areas until 100% coverage of the city is achieved. For this case study, communes have been grouped based on their population and MSW history into the four categories (1): Densely populated areas as communes with a population over 1 million (2) Moderately populated areas as communes with a population greater than 500,000 (3) Lowly populated areas as communes with a population lower than 500,000 and (4) Communes under the PARAU project (Table 4). The suggested scenarios for an integrated Municipal waste management approach recommend starting in populated areas.

Furthermore, scenarios 5 to scenario 7 focus on incorporating waste valorization systems into the scheme with an assumption of 100% MSW collection in the city. Due to the high volume of organic waste in developing countries [63], most of them do not use incineration, and anaerobic digestion is the method of predilection for an integrated SWM [64]. Moreover, the nine long months of rain [31], result in a high humidity level in the solid waste making incineration one of the least favorable options. However, implementing anaerobic digestion on a large scale is also overlooked and often avoided by many African cities due to lack of appropriate low-technology options and lack of information regarding technical and operational processes, opportunities and challenges [65].

It is crucial to note that the definition of recyclable materials per IWM-2 include paper, glass, metal, rigid and film plastic, textiles and organics. Therefore, the recycling rates for each scenario concern these materials altogether (Table 2).

- Scenario 1: (Business as usual): This covers all the nine communes covered by the PARAU project (Gombe, Kintambo, Barumbu, Kinshasa, Lingwala, Ngiri-ngiri, Kasa-vubu, Kalamu and Bandalungwa), representing 1082.2 tons/day or 13.8% of the total MSW produced daily. This is almost equal to the quantity that was reported arriving at the landfill in 2016 [39]. Considering the lack of waste sorting and lack of waste valorization data in Kinshasa, the percentage of waste incinerated, composted, recycled, and possibly transformed into biogas is considered zero. All waste collected goes to the landfill.
- Scenario 2: MSW produced in densely populated communes (Ngaliema, Masina, Kimbanseke, and Maluku) is added to the collection scheme. The UNEP has estimated that only 4% of solid waste is recycled in Africa [4]; therefore, this scenario sets up a scheme to include waste recycling at 4%, the remaining 96% is landfilled.
- Scenario 3: In addition to the waste amount collected in the previous scenario 2, MSW produced in moderately populated communes (Lemba, N'djili, Bumbu, Kisenso, Mont-ngafula and N'sele) are added in this scenario. A waste sorting system is introduced at 10% to ease recycling activities; this allows for composting at 2%, and the recycling rate increases to 10%. The remaining 88% of waste goes to the landfill, where 10% of biogas is collected with 10% of energy recovery. The 50% collected leachate is treated at a 10% rate.
- Scenario 4: The collection coverage reaches the whole city at 100% as the remaining less populated communes (Limete, Matete, Ngaba, Selembao and Makala) are added to the scheme and sorting, recycling, and composting rates double to 20%, 20% and 4%, respectively. The remaining 76% of waste goes to the landfill, where the biogas collection rate and energy recovery from the biogas doubles and leachate treatment increases to 20%.
- Scenario 5: 30% waste is sorted, 30% recycled, 6% composted, and 2% incinerated. From the 62% of MSW going to the landfill, 30% of gas is collected, of which 30% is valorized in energy. Leachate treatment efficiency also increases to 30%.
- Scenario 6: 40% of waste is sorted, 40% recycled, 8% composted, 4% incinerated, and 2% transformed into biogas. Landfill operations improve, increasing gas collection to 40% with 40% energy recovery. Leachate treatment efficiency rate is 40%.
- Scenario 7: For the last scenario of this case study, sorting and recycling rates are assumed to be 50%. Composting, incineration, and anaerobic digestion reach a rate of 10%, 6%, and 4%, respectively. The remaining 30% received by the landfill produces biogas that is collected at 50%, of which 50% is valorized into energy. Leachate treatment efficiency rate reaches 50%.

Table 3
Key input data for MSW LCA in Kinshasa.

Input parameter	Value	Reference
Kinshasa Population	12,000,000	JICA, 2019 [32]
Population growth rate	5.5%	INS, 2017 [33]
Population in 2021	15,960,000	
Daily MSW production per capita	0.65 Kg	World Bank, 2018b [34]
Total municipal solid waste production daily	7800 Tons	Deduction
Average people/household	6	Shomba S. et al., 2015 [31]
Fuel (diesel) consumption data		
Distance transfer station to landfill	35 km	JICA, 2019 [32]
Heavy-duty vehicles numbers	28 (as of 2015)	Biey, 2015 [38]
Total Fuel consumption estimated (Current management scenario)	116,188 L/an	Webfleet, 2020 [66]
Waste management cost (USD/Ton)		
Collection	35	World Bank, 2018b [34]
Controlled landfill	10	
Composting	17.5	
Recycling	25	
Incineration	25	Assumption
Bio gasification	25	

Table 4
Communes populations, waste generation and collection percentage.

Commune category	Total Population (2017)	Municipal Solid Waste Generation		Contribution to Waste generation	Cumulative collection coverage
		Ton/day	Ton/year		
Under PARAU	1,665,020	1082	395,026	13.9%	13.9%
Densely populated	5,191,616	3375	1,231,711	43.25%	57.15%
Moderately populated	3,758,109	2443	891,611	31.33%	88.48%
Lowly populated	1,890,255	1229	448,4635	11.52%	100%

Landfill diversion rate (LDR), the percentage of the waste stream that is diverted away from final disposal, was estimated for each scenario based on the formula in equation (1) [45].

$$LDR = \frac{1 - WEL}{WES} X100 \tag{1}$$

Where; LDR is the diversion rate (%), *WEL* is the amount of waste entering the landfill and *WES* is the total amount of waste entering the system.

2.1.3. Life cycle inventory

In MSW management, basic data on population, amount and type of waste generated are crucial inputs. The key input data used in this study was compiled from various sources summarized in Tables 3–5. Based on population estimates in 2017 and per capita waste generation in developing countries, Kinshasa city generates 7800 tons of MSW daily. Transportation represents an essential part of MSW emissions and management costs in the city. The average waste management costs estimated for low-income countries by the world bank [34] were used in this study. Fuel consumption was calculated based on the number of heavy-duty vehicle rotations transporting MSW from transfer stations to landfills. The total fuel consumption was calculated using the average fuel consumption of large trucks as estimated by Webfleet in 2020 [66]. In Kinshasa, waste collection is conducted three times a week, with one rotation daily.

3. Results and discussion

3.1. Fuel consumption

Based on the number of vehicles needed to implement current MSW operations in Kinshasa (scenario 1), fuel consumption was determined by deduction in the remaining 6 scenarios. The logic "*if* … *then* …" was used, based on the quantity of MSW entering the systems. It was observed that fuel consumption rapidly increases from scenario 1 to 4, owing to waste collection increase. Once the collection coverage reaches 100% (scenario 4), the same number of vehicles, consequently the same amount of fuel, is determined to be used in scenarios 5, 6 and 7.

Fuel consumption results in Table 7 are strictly valid in the context of the scenarios criteria, but do not necessarily apply to what would be implemented in reality. The need for vehicles depends on the city's goals and strategies for MSW operations. Moreover, the number of vehicles, their types and usage significantly influence fuel consumption. Sophisticated equipment in solving more complex tasks might be needed, for operations such as incineration, anaerobic digestion, recycling etc (see Table 6).

3.2. Cost analysis

Tables 8 and 9 presents the total cost arising from each scenario. Due to the lack of detailed input prices and possible profits from MSW valorization, IWM-2 was not able to present a holistic cost-benefit analysis. The null values obtained in Table 8 are all due to missing initial input cost values and profit values of the presented waste treatment types. This discrepancy was overcome by manually calculating the MSW management cost in Kinshasa. Calculations were made based on the World Bank estimates and assumptions made in Tables 3–5. Thus, the total cost for landfilling all MSW produced in scenario 1 is estimated at 17776169.78 USD/year and 1481347.481 USD/month. This corresponds to the monthly MSW operational cost of the PARAU project, estimated at 1,400,000

Table 5
Waste generation by scenario.

	Tons/year	Collection coverage (%)
Scenario 1	395,026	13.9%
Scenario 2	1,626,737	57.15%
Scenario 3	2,518,348	88.48%
Scenario 4	2,966,811	100%
Scenario 5	2,966,811	100%
Scenario 6	2,966,811	100%
Scenario 7	2,966,811	100%

Table 6
Baseline data for fuel consumption manual calculations.

Average heavy duty vehicle diesel consumption	38 L/100 km (0.38 L/km)
Average distance landfill-collection	35 km
Daily rotation amount	2
Weekly rotation amount	3
Yearly rotation amount	312
Current number of heavy duty vehicles	28

Table 7
Estimated fuel consumption.

	Estimated number of vehicles	Fuel consumption (L/year)	Fuel consumption (L/month)
Scenario 1	28	116188.8	9682.4
Scenario 2	115	478471.315	39872.60958
Scenario 3	179	740720.5222	61726.71018
Scenario 4	210	872626.7216	72718.89347
Scenario 5	210	872626.7216	72718.89347
Scenario 6	210	872626.7216	72718.89347
Scenario 7	210	872626.7216	72718.89347

Table 8
IWM-2 Cost analysis (US dollars/year).

Scenarios	Collection	Sorting	Biological	Thermal	Landfill	Recycling	Total
Scenario 1	13,825,910	0	0	0	7,898,855	0	21,724,765
Scenario 2	56,935,791	0	0	0	32,527,881	0	89,463,672
Scenario 3	88,142,189	0	0	0	50,356,350	0	138,498,539
Scenario 4	100,637,987	0	0	0	59,316,510	1726	159,956,223
Scenario 5	100,637,987	0	0	1,482,885	58,268,304	2589	160,391,764
Scenario 6	100,637,987	0	0	2,965,769	57,220,097	3451	160,827,304
Scenario 7	100,637,987	0	0	4,448,028	56,164,971	8628	161,259,615

Table 9
Scenarios cost estimations by manual calculations.

	Total cost	Total cost	Cost per person		Cost per household	
	dollars/year	dollars/month	dollars/year	dollars/month	dollars/year	dollars/month
Scenario 1	17776169.78	1481347.481	10.67625	0.8896875	64.0575	5.338125
Scenario 2	79729757.85	6644146.488	11.62811587	0.9690096554	69.76869519	5.814057933
Scenario 3	117480945.9	9790078.827	11.0677125	0.922309375	66.406275	5.53385625
Scenario 4	143296983.4	11941415.28	11.459175	0.95493125	68.75505	5.7295875
Scenario 5	147598859.7	12299904.97	11.8031875	0.9835989583	70.819125	5.90159375
Scenario 6	151307373.8	12608947.81	12.09975	1.0083125	72.5985	6.049875
Scenario 7	152790779.4	12732564.95	12.218375	1.018197917	73.31025	6.1091875

Euros/month.

Kinshasa city plans to introduce a sanitation tax withdrawn from either electricity or water bills [6]. Therefore, the expected burden of each MSW management scenario on households and individuals will steadily increase with the amelioration of waste treatment conditions. This justify the MSW management cost estimation per individual and households, shown in Table 9. This does not take into

Table 10
Landfill diversion rate.

	Total waste produced (tons/year)	Total waste landfilled (tons/year)	Diversion rate (%)
Scenario 1	395,026	395,026	0
Scenario 2	1,626,737	1,561,667	4
Scenario 3	2,518,348	2,216,146	12
Scenario 4	2,966,811	2,254,777	24
Scenario 5	2,966,811	1,839,423	38
Scenario 6	2,966,811	1,364,733	54
Scenario 7	2,966,811	890,043	70

account the possible financial benefits generated from green energies and valuable materials obtained from MSW valorization, consideration of financial benefits from MSW management influences the overall cost.

It is crucial to consider that, although scenario 1's manually estimated costs are similar to the one of PARAU project, the projected costs of remaining scenarios are gross estimations, based on scale enlargement of scenario 1. Therefore, the accuracy of manually estimated costs, from scenario 2 to 7, lies in the strict limits of this study's scope and scenarios criteria.

Thus, MSW management costs significantly fluctuate based on technologies used, amount and engine types, waste treatment types, collection frequencies, etc. Following the city's MSW management goals and stakeholders' priorities.

3.3. Landfill diversion

Landfill diversion rate results are shown in Table 10. It was observed that this indicator steadily increases form scenario 1 to scenario 7. This increase is attributed to the introduction of various MSW valorization streams throughout the scenarios. Many researchers have found that the less amount of MSW is landfilled, due to MSW treatment activities' introduction, the less negative environmental impact is observed [46,47,55–57]. In this study, landfill diversion rates increase because the burden on the landfilling decreases. This implies an increase of environmental benefit from scenario 1 to 7.

3.4. Gas emissions

Greenhouse gas (GHG) emissions under different MSW management scenarios are presented in Table 11. The emissions calculated in CO_2 equivalent are based on their respective Global Warming Potential (GWP) are 1.0 for CO_2, 21.0 for methane (CH_4) and 310.0 for nitrous oxide (N_2O).

As expected, the increase of MSW collection from scenario 1 to scenario 4, causes a steady increase of GHG emissions. This is due to the criteria on which Scenario 1 to 4 are shaped, focusing less on valorizing waste and more on moving it away from the population.

GHG emissions decrease from scenario 5 to scenario 7. This is because at this point, all MSW is collected and there is a higher emphasis on waste treatment and valorization. In these scenarios, the burden on the landfill decreases with improved waste treatment conditions.

It is observed that scenario 1 emits the least amount of GHG. This is because of its lowest MSW collection rate. In scenarios where all MSW produced is collected, scenario 7 emits the least amount of CO_2 equivalent, this is due to the improvement of waste treatment conditions and the increase of landfill diversion rate. Scenario 4 emits the most CO_2 equivalent. This is explained by the maximal MSW collection implemented, however almost all waste collected is landfilled with little to no treatment.

3.5. Water contamination

IWM-2 caters for evaluation of over 25 kinds of chemicals in water bodies resulting from waste management activities. This includes Zinc, Sulphite, Sulphate, Phosphate, Nitrate, Nickel, Mercury, Lead, Copper, Iron, Fluoride, Dioxins/furans, Cyanide, Cadmium, Barium, arsenic, Ammonium, Aluminium, etc.

However, to keep the manuscript concise, we have displayed only COD and BOD as major indicators of biological and chemical pollution altogether in Table 12. The BOD/COD ratio indicates the biodegradability, thus the pollution level of leachate generated by landfills. For leachate, the lower this ratio is, the higher the quantity of inorganic matter it contains. This implies a high toxicity level. The higher the ratio is, the more biodegradable the leachate is. Thus, BOD and COD are key parameters to guide solid waste managers in protecting water bodies receiving leachate shed from landfills [67]. In this study, the ratio of BOD to COD was equal to 1 in almost all the scenarios. This is a reflection of the MSW composition in Kinshasa, where 65% of waste represents biodegradable waste.

BOD and COD concentrations increase with MSW collection coverage and landfill rate due to the increasing amount of wastewater generated, by higher quantity of waste landfilled. With better landfill performance (improved leachate collection and treatment efficiency), less wastewater release lessens water contamination, hence the reduction of BOD and COD from scenario 4 to scenario 7.

4. Conclusions

This study applied Life Cycle thinking in MSW management of Kinshasa city and assessed six different scenarios using the current situation as a baseline. Each scenario aims to ameliorate the previous one, following national and international goals, guidelines and

Table 11
Air emissions (greenhouse gas in Tons CO_2 equivalent).

Scenario	Collection	Sorting	Biological	Thermal	Landfill	Recycling	Total
1	359	0	0	0	640,314	0	640,673
2	1,48	0	0	0	2,636,845	0	2,638,325
3	2291	0	0	0	3,758,643	0	3,760,934
4	2699	5	0	3	4,039,788	−92	4,042,402
5	2699	5	0	56,801	3,571,574	−5578	3,625,501
6	2699	5	0	113,6	3,112,322	−11,064	3,217,561
7	2699	9	0	170,333	2,679,230	−16,781	2,835,491

Table 12
COD and BOD (tons).

Parameter	Activity	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6	Scenario 7
COD	Collection	0	0	0	0	0	0	0
BOD		0	0	0	0	0	0	0
COD	Sorting	0	0	0	0	0	0	0
BOD		0	0	0	0	0	0	0
COD	Biological	0	0	0	0	0	0	0
BOD		0	0	0	0	0	0	0
COD	Thermal	0	0	0	0	0	0	0
BOD		0	0	0	0	0	0	0
COD	Landfill	133	549	807	900	833	768	705
BOD		133	549	807	900	833	768	705
COD	Recycling	0	0	0	0	0	0	1
BOD		0	0	0	0	0	0	1
COD	Total	133	549	807	900	833	768	706
BOD		133	549	807	900	834	769	706

policies. Fuel consumption, total management cost, landfill diversion rate as well as air and water contamination were estimated for each scenario.

This study finds that the optimization of the Municipal Solid Waste management system in Kinshasa city, by increasing waste collection coverage and implementing diverse streams of waste valorization, causes a decrease of atmospheric pollution in terms of CO_2 equivalent by half, when all waste is collected, and a landfill diversion increase up to 70%. Several researchers using Life Cycle Assessment approach to improve MSW management, have similarly demonstrated that, a focus on increasing activities such as recycling, composting, and enhancing conditions in sanitary landfills through methane captivation and energy conversion, significantly decreases the environmental impacts [46–48]. However, this study finds that the overall MSW management cost increases by almost 8 times more than the estimated current management cost, when environmental impact is the least. These expected results are due to the scale enlargement of MSW operations, as a larger area of the city is served (more engines are used, more rotations for collection are effectuated, more technologies are needed, etc.).

This study concludes that for Kinshasa, scenario 4 is the most realistically implementable one, considering the current socio-economic situation of the city, as well as stakeholders' priorities. Nonetheless, scenario 7, despite its high operational cost, is determined to be the most environmentally friendly for the city.

As stated by JICA, simply copy-pasting MSW management technologies and systems from developed countries to developing countries is often ineffective because methods applied by developed countries and provided in their literature are usually expensive and too sophisticated to implement [22]. In the case of cities such as Kinshasa, with a booming population and unplanned urbanization, installing a simple waste collection system can be challenging. Sorting from source, which would simplify recycling activities, is not only a matter of budget attribution but also an issue of lack of environmental awareness, environmental education programs and clear MSW policies. The UNEP suggests that African countries ensure 100% collection coverage in all cities with a population of more than 1 million and close large open dumps replacing them with controlled disposal facilities as initial technical steps to achieving better MSW management standards [16]. In Kinshasa, as in many other African megacities, specific policies for MSW are yet to be implemented. Waste management knowledge is low, more accurate data is unavailable, and responsibilities have not been clearly established. This study recommends that each of the 24 communes creates its own MSW management programs, guidelines and data collection and management to assist the provincial government and its technical organ (Raskin) in elaborating narrowed-down policies and regulations. The involvement of the private sector is crucial in the effort on enhancing MSW systems in Kinshasa. Thus, the current top-down approach should be replaced with horizontal cooperations. This will significantly help overcome the issue of lack of precise guidelines, lack of data and accountability.

Although results from the study cannot provide conclusions on the best way to improve MSW management in Kinshasa, it sets the important initial steps to conduct further research in the domain, as it is one the first LCA applied in the MSW of Kinshasa city.

5. Limitations of the study

This study has several limitations, that are presented as follow.

- Limited access to MSW related data of Kinshasa,
- Absence of previous MSW LCA research in the geographical context of this study
- Features of the utilized LCA program for this study

The results of this study are highly dependent on the validity and amount of data inputted. Limited published data on MSW management of Kinshasa city were available. Although data such as population per commune, MSW management cost, MSW production and composition, number of vehicles currently utilized and distance to landfill were defined, other key data such as engine types and their fuel consumptions, waste collection efficiency, recycling, composting, bio gasification and incineration rates, as well as possible monetary benefits from existing MSW valorization streams, were not available. The scarcity of accessible and precise MSW data in Kinshasa, is one of the reasons why no LCA, to the best of the authors' knowledge, has been previously conducted in the region. This causes major difficulties in the development and enhancement of Kinshasa's MSW management system, in regards to defining related policies and improving decision making.

To overcome these challenges, several assumptions have been made, as well as the use of global and continental estimations and averages from the literature.

Due to lack of clear policies and defined stakeholders's goals for MSW management in Kinshasa, assumptions for waste collection, sorting, recycling, composting, incineration and biogas production rates, have been set based on international goals and standards, as well as the authors appreciation. The authors recognize that some of the waste treatment rates in the proposed scenarios are too ambitious, considering the current socio-economic situation in Kinshasa. Although the process in enhancing MSW management in the city might follow the same tendencies as of this study's findings, in terms of environmental impact and cost, the results obtained are strictly function of the scope and scenarios criteria of this research.

Therefore, this study results should be used for MSW management system improvement in Kinshasa, and not exclusively as a basis for its final decision making.

The program chosen for this research (IWM-2) has no built-in sensitivity analysis function. It also only considers emissions to air and water. This implies that results based on the same scenarios criteria, using a different program, would be sensibly different. Nonetheless, its MSW specific LCA, its ability to orientate decision making from a strictly waste oriented point of view as well as its availability to the authors, justify the choosing of IWM-2.

Author contribution statement

Yllah Kang Okin: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Yabar Helmut Friedrich: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.

Mizunoya Takeshi; Yoshiro Higano: Contributed reagents, materials, analysis tools or data.

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6. Data availability statement

Data will be made available on request.

7. Declaration of interest's statement

I declare that this article is self-funded and there are no conflicts of interest among all the authors.

Additional information

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