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RESEARCH ARTICLE

Environmental impact assessment of the current, emerging, and alternative waste management systems using life cycle assessment tools: a case study of Johannesburg, South Africa

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Abstract

Proper information regarding the performance of waste management systems from an environmental perspective is significant to sustainable waste management decisions and planning toward the selection of the least impactful treatment options. However, little is known about the environmental impacts of the different waste management options in South Africa. This study is therefore aimed at using the life cycle assessment tool to assess the environmental impact of the current, emerging, and alternative waste management systems in South Africa, using the city of Johannesburg as a case study. This assessment involves a comparative analysis of the unit processes of waste management and the different waste management scenarios comprising two or more unit processes from an environmental view. The lifecycle boundary consists of unit processes: waste collection and transportation (WC&T), material recycling facilities (MRF), composting, incineration, and landfilling. Four scenarios developed for the assessment are S1 (WC&T, MRF, and landfilling without energy recovery), S2 (WC&T, MRF, composting, and landfilling with energy recovery), S3 (WC&T and incineration), and S4 (WC&T, MRF, composting, and incineration). Based on the result of this study, MRF is the most environmentally beneficial unit operation while landfill without energy recovery is the most impactful unit operation. The result further revealed that no scenario had the best performance across all the impact categories. However, S3 can be considered as the most environmentally friendly option owing to its lowest impact in most of the impact categories. S3 has the lowest global warming potential (GWP) of 33.19×10^6 $kgCO_2eq$, ozone depletion potential (ODP) of 0.563 kgCFC-11e, and photochemical ozone depletion potential (PODP) of 679.46 kgC_2H_2eq. Also, S4 can be regarded as the most impactful option owing to its highest contributions to PODP of 1044 kgC_2H_2eq, acidification potential (AP) of 892073.8 $kgSO_2eq$, and eutrophication potential (EP) of 51292.98 $MaxPO4^{-3}eq$. The result of this study will be found helpful in creating a complete impression of the environmental performance of waste management systems in Johannesburg, South Africa which will aid sustainable planning and decisions by the concerned sector.

Keywords Emission · Environmental impact · Johannesburg · Life cycle assessment · Sustainability · Waste management

Introduction

The consequences of the upsurge in the world population are rapid industrialization, urbanization, and economic growth, which are the main contributors to the swift rise in the quantity of municipal solid waste (MSW) generated globally. According to a world bank report, about 2.01 billion tonnes of waste was generated in 2016 and is projected to increase to about 3.40 billion tonnes by 2040. Since the causal components of waste generation persist in the biosphere, the environmental burden of this ever-increasing waste cannot be underestimated (Adeleke et al. 2021). For this reason, sustainable waste management has become a topic of interest in the academic space and public investment (Khandelwal et al.

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2019a). The generated waste are poorly managed thus leading to many environmental issues such as global warming, ozone depletion, human health hazard, abiotic resource depletion, and ecosystem damage among others (Khandelwal et al. 2019a). Landfill remains the most prominent method of waste disposal globally, despite the improvement in the treatment of MSW in some developed countries and landfill being the least preferred option in the waste management hierarchy (Bhada-Tata and Hoornweg 2012). The landfill is believed to be a prodigious global anthropogenic source of methane gas with global warming potential that is 21 times higher than that of carbon dioxide, and endangers the environment and human health by polluting the soil and groundwater (Couth and Trois 2012; Duan et al. 2015; Kapelewska et al. 2019; Olusheyi et al. 2020).

The complexity of the waste management system has imposed more stringent regulations and technical waste treatment options which prioritizes the protection of the environment and human health (Arena et al. 2015). In achieving a sustainable waste management system, no standalone treatment option can be suitable for all kinds of waste streams. Some fractions of waste cannot be reused, recycled, or biologically treated after being collected separately. Thus, they must be properly treated to save the environment and human health and recover energy (Brunner and Rechberger 2015). In recent years, the transition from a linear economy to a circular economy has been gaining traction through the prevention of waste, efficient reuse, and recovery of materials and energy. With this trend, under the present proposal, recyclables materials will be restricted from being landfilled by the EU in 2025, while all disposal by landfill will be banned by 2030 (Jeswani and Azapagic 2016). Integrated waste management that involve environmental-friendly options such as composting, recycling, and anaerobic digestion is gaining traction in most developed countries and has been proven to portray a better environmental performance (Chen et al. 2019; Wang et al. 2020).

Implementing the different options of integrated waste management systems sustainably requires a proper understanding of the environmental performance of the options. The environmental impacts of waste management systems have been extensively researched using the life cycle assessment (LCA) tools considering all inputs and outputs of materials and energy from cradle to grave, i.e., from production to disposal (Erses Yay 2015; Jeswani and Azapagic 2016). The LCA is a computer software tool that is globally accepted for assessing the potential impacts of waste's life cycle on the environment using several standards and simplified methods such as Eco-inventor 99 and CML 2001 with software such as GaBi, SIMAPRO, openLCA among others (Khandelwal et al. 2019a; Pujara et al. 2019). A comparative assessment of different waste management alternatives through LCA methodology supports critical decisions in waste management by providing an analytical framework and quantitative assessment of waste management, identifying the most impactful and less impactful systems, and suggesting ways to improve the environmental performance (Bartolozzi et al. 2018; Christensen et al. 2020). The literature is replete with researches that applied the LCA tools in evaluating waste treatment techniques from an environmental perspective in various countries. The abundance of LCA studies in the literature revealed its wide acceptability as a reliable tool for assessing the environmental impact of waste management systems.

A comparative assessment of the environmental impact of four waste management scenarios in Nagpur city, India, involving composting, materials recovery facilities (MRF), anaerobic digestion, and landfill using LCA tools was carried out by Khandelwal et al. (2019b). Based on his result, a scenario that combined MRF, composting, and landfill was found to be the least environmentally impactful option. The study of Ta and Demir (2020), which evaluated the environmental and energy impact of the present waste collection and transportation system and three other alternatives in Kayseri city, Turkey, revealed that the construction of transfer stations instead of landfill sites reduced the environmental impact in all impact categories and the cumulative energy demand (CED). A similar study was carried out in the city of Brasilia, Brazil by Silva et al. (2021), which considered four scenarios that incorporate the production of refuse-derived fuel (RDF) in the existing system. It was revealed that the scenario which included the RDF production increased energy demand and greenhouse (GHG) emission against the current waste management scenario. Noya et al. (2018) revealed, through an LCA comparative study in the city of Kazakhstan, that the reuse of recycled materials immensely reduced the environmental burden and energy generation, consequently making the proposed waste management scenarios more environmentally friendly.

A reduced environmental impact of waste management option which considers materials recycling and energy recovery was reported from an LCA study by Ferronato et al. (2020) as a basis for cooperative framework in Bolivia. The study of Khan (2021) was aimed at utilizing LCA methodology to compare the global warming potential (GWP) of cement production and the related waste management using the conventional fuel and solid recovered fuel (SRF) partly substituted fuel. Four scenarios based on different waste treatment techniques were developed with a different mix of SRF in the thermal energy mix in cement production. A 20% reduction in the GHG emission was reported from 1036 $kgCO_2eq$ in scenario 1 to 832 $kgCO_2eq$ in scenario 3. Street sweeping which is an integral part of waste management is often neglected in most LCA studies. Thus, Bartolozzi et al. (2018) analyzed different street sweeping systems in Italian cities using LCA tools and revealed that fuel consumption had the greatest environmental impact. The value chain of the waste management system in Rawalpindi waste management company in Pakistan was studied by Atta et al. (2020) to investigate its environmental burden. Using a functional unit of 1 tonne of MSW, the study revealed that the company contributed 8962.8 kg1,4-DBeq per tonne of MSW, 15.79 kgCO_2eq per tonne of MSW, 6.22 kg1,4-DBeq per tonne of MSW to marine ecotoxicity, GWP, and aquatic ecotoxicity potential respectively. The study by Haupt et al. (2018) opined that the system boundary in most studies is limited to one tonne of waste or a particular waste system, hence proposed an assessment framework that considers the actual flow of waste in a detailed material flow analysis (MFA) for a complete waste management assessment.

To establish a more environmentally sustainable waste management option in China, Liu et al. (2021) analyzed the present waste management options in Hohhot city, China. The study showed that the scenario which combined the landfilling and incineration in the ratio 1:5 had the best and optimal performance environmentally. However, an increase in the quantity of incinerated waste increased the GWP of the scenario. The application of LCA tools for environmental impact analysis was extended to pre-collection, collection, and transportation of MSW in urban by Perez et al. (2020). It was revealed in the study that pneumatic system of collection and transportation contributes more to climatic change, acidification, particulate matter, and stratospheric ozone depletion while underground container contributes more to terrestrial eutrophication and photochemical ozone formation. Possible scenarios comprising of anaerobic digestion, material recovery, and production of secondary fuel in Caserta province, Southern Italy, was evaluated using different environmental parameters by Cremiato et al. (2018). The option with the highest rate of waste separation at the source was observed to have the lowest impact in all the parameters considered for evaluations.

Integrated waste management systems in the city of Horqin Left Rear, Inner Mongolia Province, China was assessed by Wang et al. (2020) from an environmental and economic perspective using combined life cycle cost (LCC) and LCA analysis. The greatest contribution of integrated waste management to the environmental burden in the case study was obtained from treatment options including MSW separation, brick making, and plastic recycling. The study further revealed that an increase in the ratio of waste separation reduces the total environmental and economic burden. Rizwan et al. (2019) evaluated the environmental performance of MSW processing in Abu Dhabi Emirate and reported that recycling of waste and production of bio-ethanol through gasification is the most environmentally beneficial option of the integrated waste management systems. Based on the assessment of waste-to-energy (WTE) technologies by Havukainen et al. (2017), it was found that refuse-derived fuel (RDF) production and incineration have a less environmental impact compared with co-incineration with coal.

There is a need to revamp the waste management systems in South Africa to prioritize treatment options that minimize the overall environmental burden of the waste management systems. As result, more attention on the environmental impact assessment of the waste management systems in South Africa through LCA has become necessitated. Implementing future alternatives sustainably and understanding the total environmental performance of waste management systems requires LCA. Despite the significance of LCA studies in waste management, very limited studies were found in literature in South Africa and Africa at large. Recent worldwide critical reviews on LCA applications in the environmental assessment of waste management systems by Khandelwal et al. (2019a), Iqbal et al. (2020), and Zhang et al. (2021) also revealed the scantiness of LCA studies in waste management in low-income regions, especially in African countries. Most of these studies were focused on high-income and medium-income countries but their results do not apply to the local context of the South African waste management system, owing to the peculiarities of waste quantities, characteristics, and treatment methods. The studies by Friedrich and Trois (2011), Friedrich and Trois (2013), Friedrich and Trois (2016), and Couth and Trois (2011) have contributed immensely to GHG emission factor accounting in waste management unit operations in South Africa. However, the application of LCA methodology for a comparative assessment of different waste treatment alternatives in South Africa needs to be researched extensively. This study is therefore aimed at using the LCA tools to evaluate the environmental impact of the current, emerging, alternative options of integrated waste management in South Africa, using the city of Johannesburg as a case study. This assessment involves the comparative evaluation and analysis of the unit processes and activities that are associated with the current and emerging, and future waste management scenarios from an environmental impact point of view in Johannesburg city. The analysis was carried out based on the unit process of waste management in the city as well as different management scenarios developed comprising two or more unit processes. The potential environmental benefit of phasing-out the landfilling of mixed waste in the future alternative waste management scenarios in Johannesburg was investigated. The result of the study will support waste-related decisions toward implementation, improvement, policy formulations, and strategic planning of waste management toward an optimal environmental benefit in the city of Johannesburg.

Materials and method

Study area

The city of Johannesburg (CoJ) is located in the Gauteng province. It is the constitutional headquarters of South

Africa, geospatially located at latitude 26°12′08″ S and longitude 28°02′37″ E with an area of 1645 km^2 and an elevation of 1767 m. The Johannesburg area is composed of crystalline rocks of Archean age which is grouped as granitic rocks, metasediment and metavolcanic. The landscape of the city is marked by elongated ridges, rolling topography, and wide plain areas (Abiye et al. 2011). The city is one of the three metropolitan cities in Gauteng province representing about 85 % of the population in the province. Johannesburg is often referred to as the economic hub of South Africa because it contributes the highest gross domestic product (GDP) (17% of South African GDP and 47% of Gauteng Province's GDP) and employment in South Africa (Mbuli 2015). Pikitup Company formed in 2001 operates the waste management, collection, and disposal in the city (Mbuli 2015). Pikitup manages the quantity of waste generated in the city with the following facilities: 11 waste depots, 42 garden sites which are also used as buy-back centers with 18 additional buy-back centers and 4 landfill sites. There are two different sources from which Pikitup Company in Johannesburg collect waste. The daily non-compacted (DNC) waste is collected daily from hotels, food restaurants, and stores. The round collected refuse (RCR) is collected weekly from residential buildings. The impressive economic growth of the city has attracted migrations into the city and caused an upsurge in the population. Consequently, the quantity of waste generated has increased over the year. Figure 1 represents the maps of South Africa, Gauteng province and Johannesburg, showing some waste management facilities of Pikitiup Company. Based on the characterization study done by Ayeleru et al. (2018), the waste generated in Johannesburg comprised plastics (22.6%), organics (21.4%), paper (16.2%), metal (6.7%), and textile (6.4%). Other characteristics of waste generated in the city of Johannesburg are represented in Tables 1 and 2.

LCA methodology

The method used for the LCA study was based on ISO 14040 (2006) guidelines in four stages, namely (i) goal and scope, (ii) inventory analysis, (iii) impact assessment, and (iv) interpretation.

Goal and scope

The study is aimed at assessing the environmental impacts of the current, emerging, and future alternatives of waste management systems in South Africa, using the city of Johannesburg as a case study. The consequential LCA approach using SIMAPRO version 9.1.1.1 software was used to achieve this goal because of the potential consequences of the alterations of the waste management system on technology and society.

Functional unit and system boundary

The functional unit of the system in this study is 1 tonne of waste from cradle to grave (generation to disposal). The composition of one tonne of waste is presented in Tables 1 and 2. The following assumptions were made in this study:

- The physical composition of the waste does not change in the present and future scenario using a 10-year time-horizon.
- The collection rate in the present scenarios is assumed to be uniform in other alternative scenarios.
- Due to the unavailability of data, emission to the soil was not considered.
- All treatment facilities are assumed to be located in the same place.

Solid residues of incineration in future alternatives are proposed to be diverted for alternative uses in road and building construction sites. However, the impact of the non-solid residues was considered in the impact assessment of incineration as a unit process. The flow of material and energy used to quantify unit operations in the system is depicted by the system boundary in Fig. 2. The system boundary encloses the collection and transportation, MRF, composting, and incineration. Landfilling is the unit operation that ends the boundary.

Table 1 Elemental and proximate analysis of waste generated in Johannesburg

Elemental analysis			Proximate analysis		
Properties	Range (%)	Average (%)	Properties	Range (%)	Average (%)
Carbon (C)	45.25–45.39	45.32	Ash	5.39–5.42	5.41
Hydrogen (H)	6.18–6.25	6.22	Moisture content	60.92–67.10	63.93
Nitrogen (N)	1.96–2.04	2	Volatile matter	21.78–23.00	22.55
Sulfur (S)	0	0	Fixed carbon	4.41–11.91	8.16
Oxygen (O)	41.00–41.12	41.06			
C: N	–	22.66			

Adapted from Ayeleru et al. (2018)

Table 2 Physical composition of waste generated in the city of Johannesburg

Waste stream	DNC (wt. %)	RCR (wt. %)	Average (wt. %)
Paper	18.95	13.45	16.2
Plastics	26.95	18.15	22.6
Textile	4.95	7.75	6.4
Metal	8.45	4.85	6.7
Organic	13.85	28.70	21.4
Glass	9.4	6.25	7.8
Others	19.7	18.2	18.9
Other characteristics	**DNC (w/w) %**	**RCR (w/w) %**	**Average (w/w) %**
Recyclables	37	25.0	31.0
Potential Recyclables	40.5	47.0	43.8
Non-recyclables	22.5	28.0	25.3

Adapted from Ayeleru et al. (2018)

Scenarios description

Scenario 1 (present waste management system) This scenario represents the status quo waste management option in the city of Johannesburg. A larger percentage of collected waste is disposed of in landfills. Not all recyclables are recovered. However, only about 10% of the collected mixed waste (27% of all recyclables) are treated and recycled using the MRF, while the remaining 90% are disposed of in landfills without gas capture for energy recovery and electricity generation.

Scenario 2 (emerging waste management system) In this system, the organic fraction of the waste is treated and converted

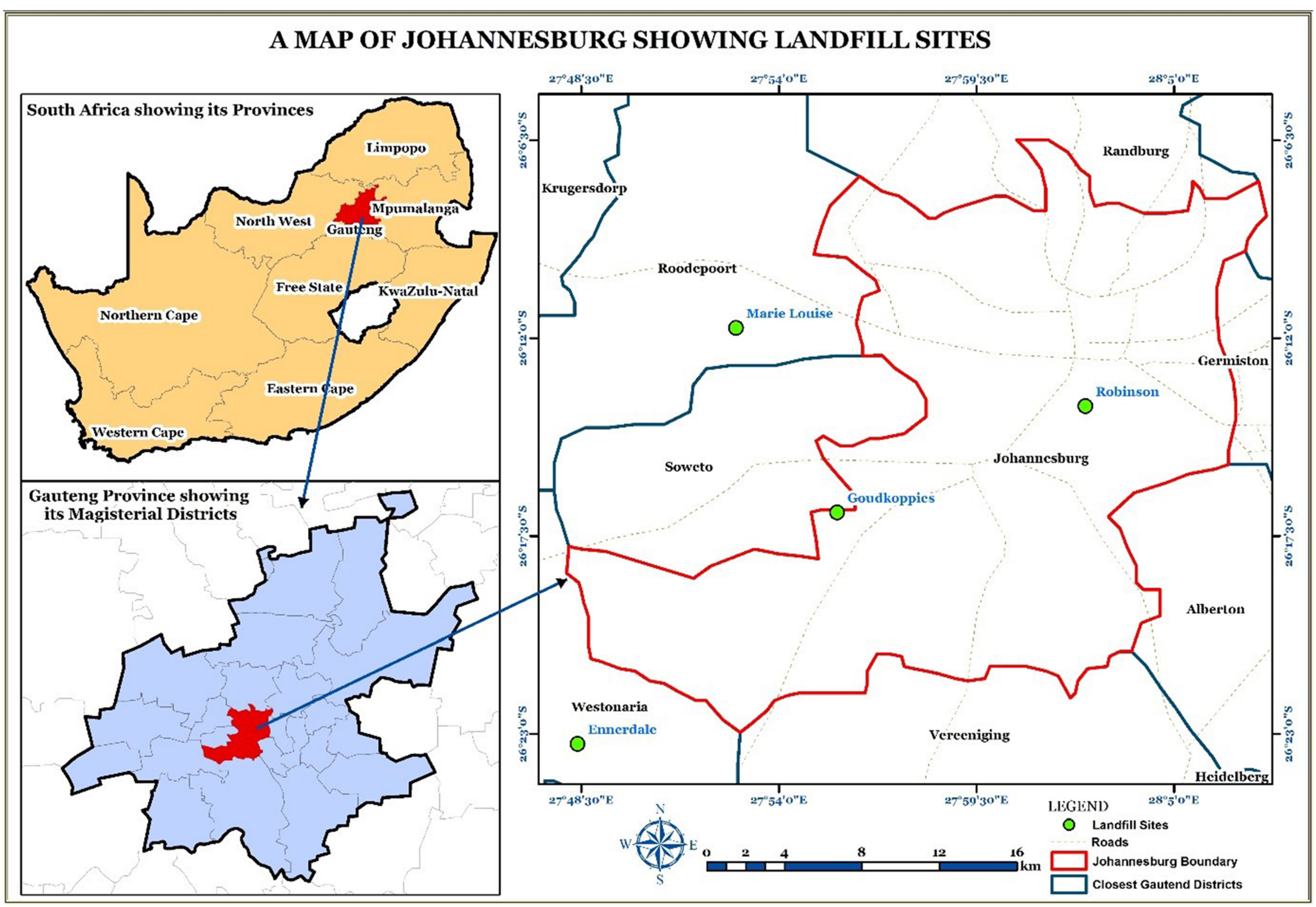

Fig. 1 Map of South Africa, Gauteng province and Johannesburg, showing the major landfill sites

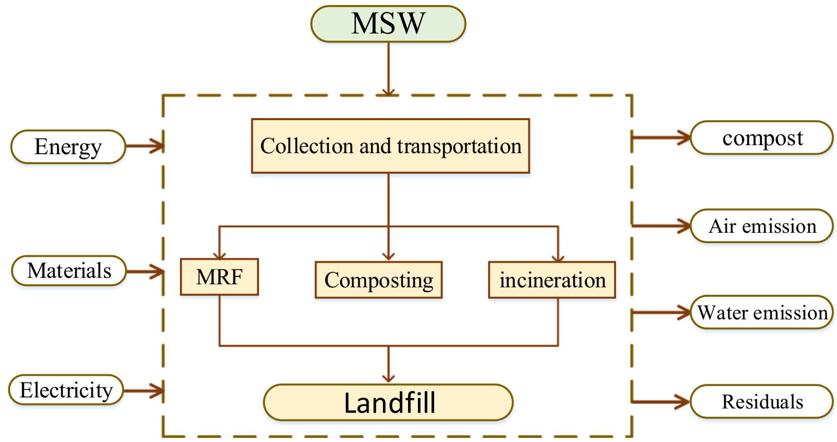

Fig. 2 System boundary

into useful materials through composting while the actual fraction of recyclables (37% of the collected mixed waste) in the mixed waste streams namely metal, plastic, paper, and glass are treated at the MRF. The rejected and non-recyclable waste is disposed of in engineered landfill sites. Methane gas is recovered at the landfill and utilized to generate electricity. This is an emerging and promising practice in the city of Johannesburg which has been operational but not yet in its full capacity.

Scenario 3 (alternative waste management system) A future waste management option where all collected waste is mass burnt in the incineration plant was proposed. This option explores the opportunity of phasing-out the landfilling of mixed waste streams through the incineration of all collected waste. Solid residues of incineration are diverted for alternative uses in road and building construction sites.

Scenario 4 (integrated waste management system) The integrated waste management systems incorporate all the unit processes of waste management involving the recovery of the all-recyclable fraction of waste (37% of collected waste), composting all organic waste (23% of collected waste), and the incineration of combustible and other rejected waste streams (40% of collected waste). This option also explores the opportunity of reducing the quantity of waste that is disposed of in landfill sites. Table 3 and Fig. 3 further describe quantities of waste and flow of materials in each scenario.

Life cycle inventory

The life cycle inventory data was gathered from Pikitup Company, waste characterization, and emissions report in the city of Johannesburg from relevant literature, Joburg city emission reports, and SIMAPRO database. All inventory data were normalized per tonne of waste. Life cycle inventory involves the identification and quantification of energy and materials flows in and out of the system boundary. About 1.4 million tonnes of waste are collected by Pikitup Company. Direct fuel consumption data for collection and transportation are scarcely available in most South African municipalities. Only 33.8% of South African municipalities have proper custody of information on transportation and collection of waste. However, Friedrich and Trois (2013) estimated the average fuel consumption for waste collection based on the expenses on fuel for waste by some municipalities and the average fuel price for the year. The total annual consumption was then divided by the amount of waste delivered to the landfill site to obtain the fuel consumption per tonne of waste.

Based on this estimate, fuel consumption for waste transportation is 5 L of diesel per tonne of waste. The emission factor for waste collection and transportation can be estimated from the measured quantity of fuel consumption. The emission factor for waste collection trucks in South Africa is 15 kgCO_2e/tons of waste (Friedrich and Trois 2013). The average distance of a collection vehicle trip from collection points to landfill sites is about 11.2 km. Here, it is assumed that all

Table 3 Waste quantities in each unit operations across all scenarios

Scenarios	Collected (×10^3 tonnes)	MRF (×10^3 tonnes)	Composting (×10^3 tonnes)	Incineration (×10^3 tonnes)	Landfill (×10^3 tonnes)
Present (S1)	1400	140 (10%)	0	0	1260 (90%)
Emerging (S2)	1400	518 (37%)	299.6 (23%)	0	582.4 (40%)
Alternative (S3)	1400	0	0	1400 (100%)	0
Integrated (S4)	1400	518 (37%)	299.6 (23%)	582.4 (40%)	0

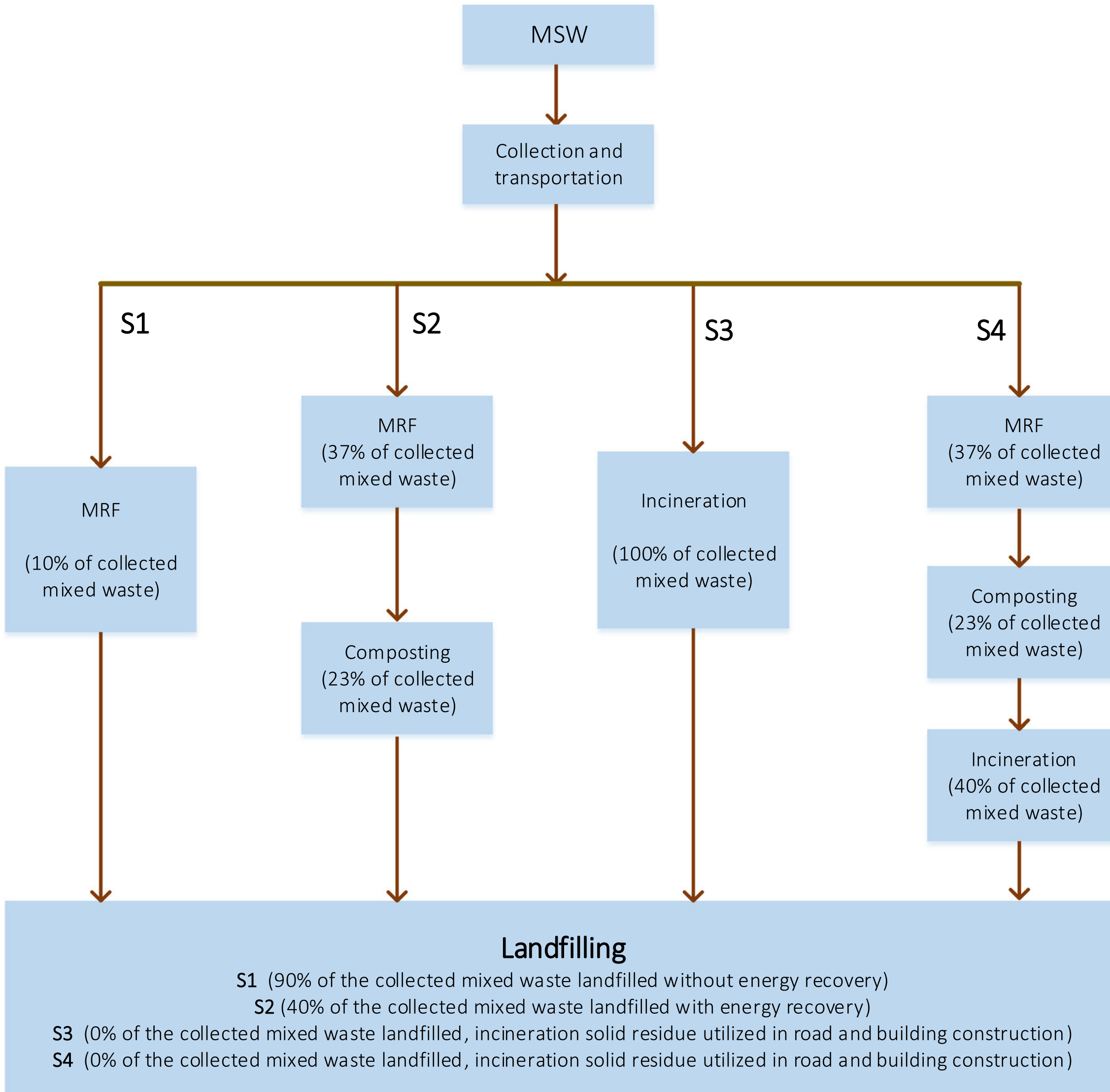

Fig. 3 Description of material flow in all the scenarios

treatment facilities are located in the same place. Also, the collection rates in the present scenario are assumed as the same in the future scenario. Hence, fuel consumption in all cases of transportation is uniform in all scenarios. Standard greenhouse gas emission from waste collection trucks was taken from Larsen et al. (2009) and normalized per tonne of waste.

The material recovery facility (MRF) which is used for sorting the collected waste into recyclables consumes 5.9 kWh per tonne of mixed waste. The facility consumes 30 L of water per tonne of mixed waste. Plastic is recycled at the rate of 46.3%, paper and metal at the rate of 42% and 70% respectively. MRF for recycling option is used in the present scenario, emerging and the integrated waste management options (S1, S2, and S4). MRF in scenarios 2 and 4 receives and treats the actual fraction of recyclable waste in the collected waste. Composting treatment option is considered for the emerging and integrated waste management system (S2 and S4). Materials and energy flow into the system are as follows: 15 kWh/tons of electricity, 2 L of diesel/tons of bio-waste, and 90 L of water/ton of bio-waste. The elemental analysis from the characterization studies of the waste in Johannesburg gives a chemical formula $C_{26.29}H_{43.79}O_{17.95}N$ and can be used to estimate emission from composting process in conjunction with guidelines provided by Global Protocol for Community-scale Greenhouse Gas Emissions (GPC) for biological waste treatment.

The mass burning of all collected waste is utilized in alternative waste management (S3) while the combustion of rejected waste and non-combustible waste is utilized in the integrated waste management option (S4). A 100% incineration of all collected waste in S3 is a future alternative waste management system in Johannesburg while in S4, only the rejected and non-biodegradable waste are sent to the

Table 4 Global warming potentials of all unit processes in all the scenarios

Global warming potential ($kgCO_2eq$)						
Scenarios/ Unit process	WC&T	MRF	Composting	Incineration	Landfill	Total
S1	3,262,096.5	411,062.43	–	–	751,878,400	755,551,558.9
S2	3,262,096.5	1,522,098.6	23,289,102.6	–	76,876,800	104,950,097.7
S3	3,262,096.5	–	–	29,928,599	–	33,190,695.32
S4	3,262,096.5	1,522,098.6	23,289,102.6	29,928,599	–	5,8001,896.51

incineration plant for treatment. However, in all cases of incineration, electricity generation is not involved. Energy input into the incineration plant is 70 kWh/ton while the emission data of waste incineration and non-solid residues were taken from the Greenhouse gas emission inventory for the city of Johannesburg.

Emission from landfill sites in S1 is not captured but rather released into the atmosphere while in S2, the gas is captured, flared, and utilized to generate electricity. Friedrich and Trois (2013) estimated the emission factor for the waste landfill in South Africa as 1291 $kgCO_2e$/ton of disposed waste. In scenario 2, landfill gas is recovered at an efficiency of 70% while the electrical output of all landfills in Johannesburg is about 19 MW at a conversion efficiency of 30%. Landfill gas with energy recovery is believed to have reduced emissions. However, the emission factor for the landfill with gas collection and electricity generation in South Africa was estimated as 131 $kgCO_2e$/tonne of disposed waste (Friedrich and Trois 2013). This is far lower than landfills without gas capture and electricity generation.

Life cycle impact assessment

In this study, the following impact categories were considered to evaluate the environmental impact of the waste management systems based on the Eco-indicator 99 method in SIMAPRO 9.1.1.1: global warming potential (GWP), ozone depletion potential (ODP), acidification potential (AP), eutrophication potential (EP), and photochemical ozone depletion potential (PODP). These impact categories were chosen based on their relevance and significance to the case study, Johannesburg. The impact categories selected are of more environmental concern in the case study. The characterization analysis of these impact categories was carried out based on the LCI result using relevant characterization factors.

Results and discussions

Global warming potential

The GWP was estimated based on 100-year characterization factors of all greenhouse gases (GHG) contributing to the GWP found in the LCI result. The characterization analysis in this study revealed that the major contributors to GWP in all the scenarios are CO_2 and CH_4. The percentage share of CO_2 and CH_4 of all total GHG contributing to GWP are 77.8% and 19.9% respectively. The concentration of CO_2 in the atmosphere is higher than the CH_4 based on the LCI result. However, methane has a higher GWP. Other substances were found to have a very low concentration in the atmosphere despite their high GWP. The fluorinated gaseous substances contributed less than 2% to the GWP in all scenarios in this study. Shown in Table 4 is the GWP of all unit processes which form each scenario.

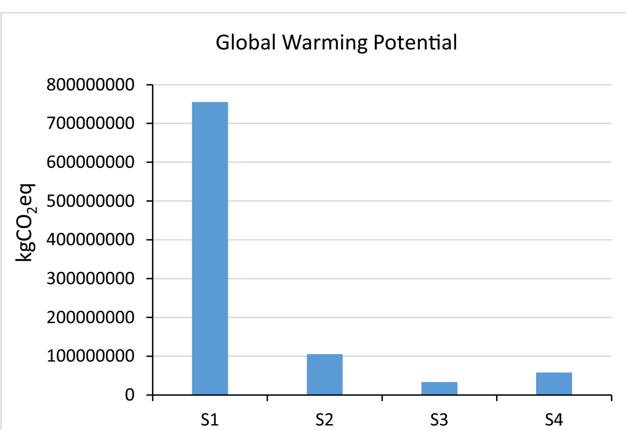

Fig. 4 Global warming potential in all scenario

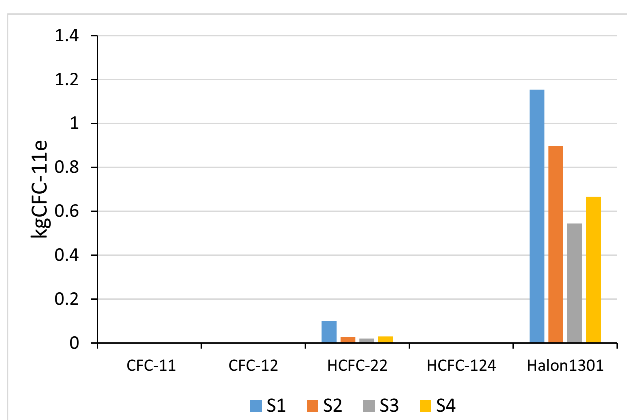

Fig. 5 Ozone depletion potential of different Substances in each scenario

Table 5 Ozone depletion potentials of all unit processes in all the scenarios

Ozone depletion potential (kgCFC-11e)						
Scenarios/unit process	WC&T	MRF	Composting	Incineration	Landfill	Total
S1	0.40705756	0.00217	–	–	0.845	1.253
S2	0.40705756	0.00803397	0.1246343	–	0.386	0.925
S3	0.40705756	–	–	0.158	–	0.565
S4	0.40705756	0.00803397	0.1246343	0.158	–	0.698

It is revealed from the table that waste collection and transportation (WC&T) follows the same trend of operations and fuel consumption and contribute the same GWP in all scenarios. Materials recovery facilities (MRF) handles a different volume of recyclable wastes in all the scenarios. However, it contributes the least to GWP in all scenarios. It is therefore a reasonable consideration in sustainable waste management systems. The impact of incineration on GWP is higher than composting. It was further revealed that landfills without energy recovery had the highest contribution to GWP which accounts for the high GWP impact in S1. Landfill with energy recovery has a relatively lower GWP impact compared to Landfills without energy recovery but makes S2 the second-largest impacting scenario in terms of GWP. Scenario 3 is the least impactful and the most environmentally beneficial option based on the GWP impact category. Figure 4 represents the overall GWP of all the scenarios depicting S1 as the most impactful scenario and S3 as the least impactful scenario based on GWP.

Ozone depletion potential

The ODP measures the extent of the impact of some emissions from waste management processes on the ozone layer. Major ozone depletion substances (ODS) which contributes significantly to the ODP in the LCI result are trichlorofluoromethane (CFC-11), dichlorodifluoromethane (CFC-12), chlorodifluoromethane (HCFC-22), 2-chloro-1,1,1,2-tetrafluoroethance (HCFC-124), and bromotrifluoromethane (Halon 1301). These substances are vital in the study of ozone recovery as well as climatic change whose extent of damage to the ozone layer depends on its chemical properties (Morales-Méndez and Silva-Rodríguez 2018). As shown in Fig. 5, Halon 1301 had the highest contribution to ODP in all scenarios. It has a high concentration in the atmosphere based on the LCI and a high ODP contributing 94.7% of the total contributions of all ODS. The concentration of CFC-11, CFC-12, HCFC-22, and HCFC-124 uniform in all the scenarios while HCFC is relatively higher with its highest concentration in S1.

Table 5 presents the ODP of each unit process in all the scenarios. The similarity of processes, waste quantity, and fuel consumption in collection and transportation (WC&T) in all the scenarios accounts for the uniformity in the ODP contributions by WC&T in all the scenarios as revealed in Table 6. MRF contributes the lowest to ODP in S1, S2, and S4 while Landfill with and without energy recovery has the highest contributions to ODP. This highest ODP of landfills without energy recovery results in the overall high ODP in S1. The result of this study confirmed the observation of Hodson et al. (2010) that the highest contribution of ozone depletion substances is from landfills. According to Hodson et al. (2010), ozone depletion substances, majorly CFC-11 and CFC-12 from landfills constitute about 0.4–1% (0.006–0.09 Gg/year) of the total emission in the USA. As shown in Fig. 6, all the waste management options in S1 emit ozone depletion substances which degrade the ozone layer the most while the S3 is the least impacting option based on ODP, though with a marginal variation. None of the options harmed the ozone layer.

Acidification potential

The release of substances with acidification effect from waste management affects both the aquatic and terrestrial ecosystems by causing acid and forest degradation (Ayodele et al.

Table 6 Acidification potentials of all unit processes in all the scenario

Acidification potential ($kgSO_2eq$)						
Scenarios/Unit process	WC&T	MRF	Composting	Incineration	Landfill	Total
S1	22,329.63	5321.92	–	–	260,568	288,219.55
S2	22,329.63	192,067.6401	301,056.0602	–	92,467	607,920.33
S3	22,329.63	–	–	377,127.163	–	399,456.79
S4	22,329.63	191,560.9853	301,056.0602	377,127.163	–	892,073.83

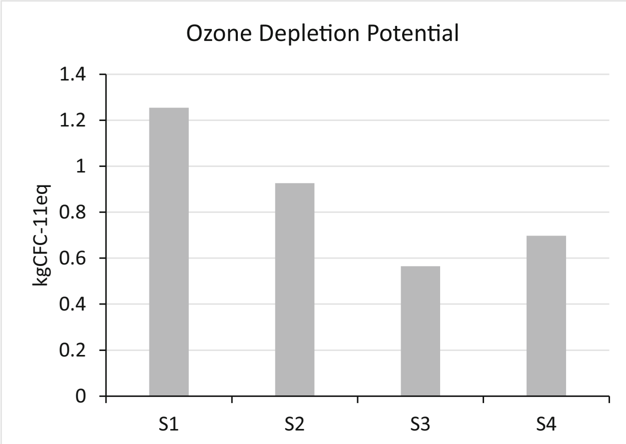

Fig. 6 Ozone depletion potential in all scenarios

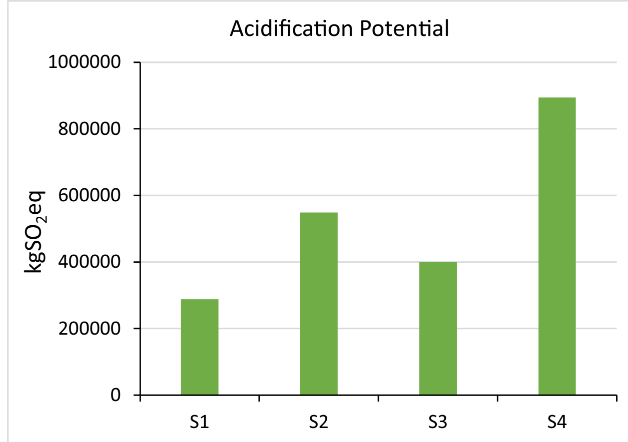

Fig. 8 Acidification potential in all scenarios

2017). In this study, substances with acidification effects that contribute significantly to AP are sulfur dioxide (SO_2), nitrogen oxides (NO_x), and hydrogen sulfide (H_2S). The acidification potential is estimated in the SO_2 equivalent. Based on the LCIA result, about 56% of AP resulted from SO_2, 22% from NO_x, and 11% from H_2S while other substances like hydrogen fluoride (HF) and nitrogen dioxide (NO_2) have a lower concentration in the emission, thereby contributing minimally to the AP. Figure 7 represents the AP of each acidification substance in each scenario.

Shown in Table 6 is the characterization result of all acidification substances in each unit operations of all scenarios. The MRF does not follow the usual trend in AP like other impact categories as it has a more acidification effect on the environment. It gives AP higher than WC&T in S2 and S4. However, MRF in S1 had the least AP. The AP in WC&T in all scenarios follows the same trend because the processes, quantity of materials collected, and fuel consumption are the same. Reduction in the quantity of landfilled materials in S2 in addition to the capture of gas for electricity resulted in a decrease in SO_2 and consequently AP. Acidification substances from landfilling have more effect on the water quality. Incineration of waste emerged with a higher concentration of SO_2 and NO_x in S3 and S4, thus resulting in higher AP in the two scenarios. Composting is another waste processing with a high AP with only a marginal difference in the AP obtained in incineration. As revealed in Fig. 8, S4 has the highest AP owing to the high acidification substances emitted in incineration and composting while S2 has the least AP.

Eutrophication potential

A high level of macronutrients comprising nitrogen and phosphorus cause eutrophication in the ecosystem. The characterization analysis of all emissions contributing to EP is based on PO_4^{3-} equivalent. Based on the LCI result, nitrogen (N), nitrate (NO_3^-), nitrogen oxide (NO_x), and chemical oxygen demand (COD) are the major contributors to EP. Figure 9 represents each substance and its contribution to AP in all the scenarios. The substance with the highest contribution to EP is the NO_x with about 48.8% share of total EP and N having 43.6% share. The larger percentage of the NO_X in S3 and S4 was due to the incineration process. The composting process emits lesser NO_x but with a concentration higher than the

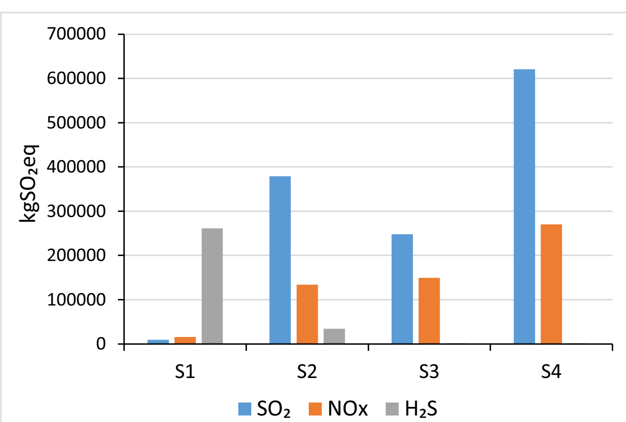

Fig. 7 Acidification potential of different acidification substances in each scenario

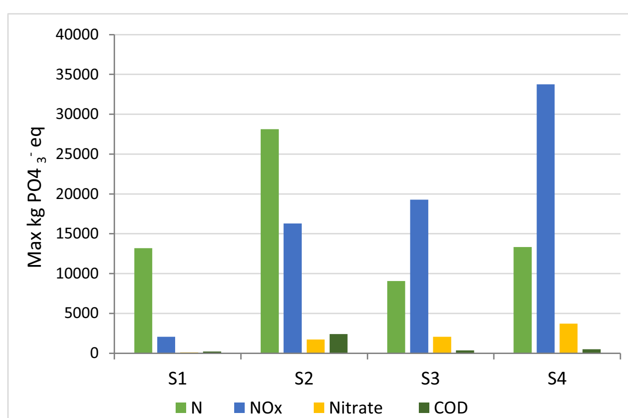

Fig. 9 Eutrophication potential of different substances in each scenario

Table 7 Eutrophication potentials of all unit processes in all the scenario

Eutrophication potential (Max PO_4^{3-} eq)						
Scenarios/unit processes	WC&T	MRF	Composting	Incineration	Landfill	Total
S1	6036.45	339.84	–	–	9208.62	15,584.91
S2	6036.46	1257.88	19,265.75	–	21,999.57	48,559.66
S3	6036.46	–	–	24,732.89	–	30,769.35
S4	6036.46	1257.88	19,265.75	24,732.89	–	51,292.98

landfill process. Leachate from the landfill is a potential source of NO_x emission, thereby contributing to EP significantly.

Presented in Table 7 is the EP for each process in all scenarios. It is revealed that MRF has the least AP across all the scenarios followed by the WC&T. Landfills without energy recovery had a higher EP than landfills with energy recovery. The incineration process has the highest EP based on the high concentration of NO_x as previously mentioned. There is only a marginal difference between EP of composting and landfill. As revealed in Fig. 10, S4 has more impact on EP more than the other scenarios.

Photochemical ozone depletion potential

Waste management processes emit volatile organic compounds which burden the environment and contribute to the creation of photochemical oxidants. Methane (CH_4), volatile organic compound (VOC), and carbon monoxide (CO) are significant to PODP as they had reasonable contributions to PODP. Based on the LCI result, the high concentration of CO and CH_4 emission was due to the incineration options in S3 and S4 which results in a higher contribution to PODP (about 55.7% of the total contributions) as depicted in Fig. 11. Landfill with and without energy recovery options in S1 and S2 emitted a higher concentration of CH_4 thereby having a high share of about 31% of the total contribution to PODP. Other substances like ethane and isoprene have a relatively lesser contribution to PODP (less than 2% of the total contribution).

PODP was characterized in each operational stage for all scenarios and expressed as ethylene equivalent (kgC_2H_4eq). Table 8 revealed that MRF is a more environmentally beneficial waste management option based on PODP because it has the lowest potential of creating photochemical oxidants. MRF in S1 has a very low PODP value of 5.97 kgC_2H_4eq followed by MRF in S2 with a PODP value of 22.1 kgC_2H_4eq. The concentration of VOC in WC&T is also significant giving a PODP value of 244.8 kgC_2H_4eq but lesser than what is obtainable in composting of organic waste fraction. The PODP in composting is far higher than the WC&T. The high concentration of VOC emitted during the composting stage in S2 and S4 can be attributed to the high PODP in composting. This also contributes to the high value of PODP in S2 and S4. Figure 12 represents the trend in the PODP values in all the scenarios. The lowest PODP was obtained in S3 while the highest PODP was obtained in S4 owing to the combination of composting and incineration processes which emits concentrated substances that contributes to PODP.

Discussion of environmental significant issues

Based on ISO (14043) standard, interpretations of the LCA result can be done in the following steps: (i) identifying the

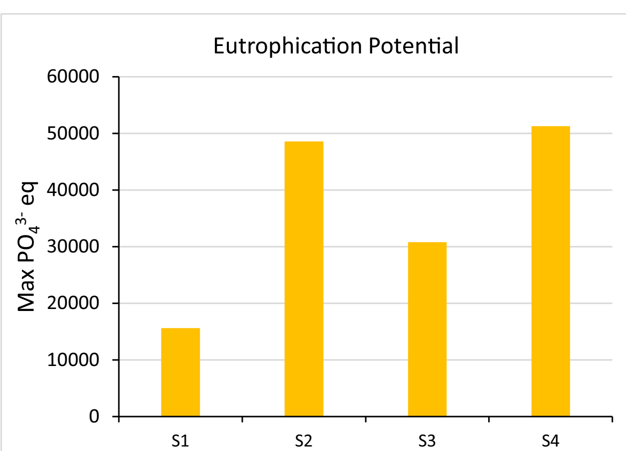

Fig. 10 Eutrophication potential in all scenarios

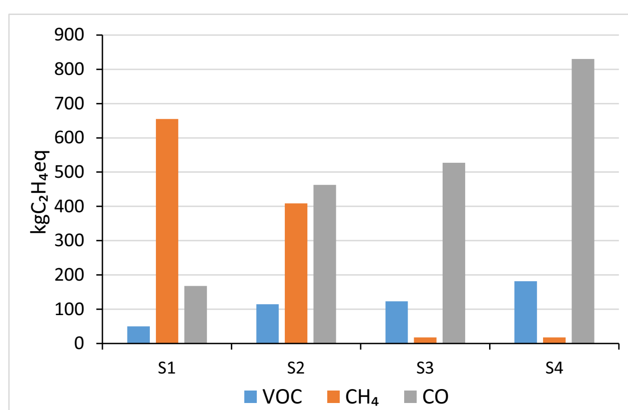

Fig. 11 Photochemical ozone depletion potential of different substances in each scenario

Table 8 Photochemical ozone creation potentials of all unit processes in all the scenario

Photochemical ozone creation potential (kgC_2H_4eq)						
Scenarios/Unit process	WC&T	MRF	Composting	Incineration	Landfill	Total
S1	244.779993	5.9741285	–	–	637.40	888.154
S2	244.77999	22.104119	342.439383	–	386.94	996.149
S3	244.7799925	–	–	434.68298	–	679.46297
S4	244.7799925	22.104119	342.439383	434.68298	–	1044.006

environmentally significant issues from the life cycle inventory data and lifecycle impact analysis, (ii) evaluating the steps taken and assumptions made in the course of LCA, and (iii) making reasonable conclusion from the evaluation (Dunmade 2012). The LCI result from the SIMAPRO simulations revealed different mass concentrations of different substances which are important from the environmental perspective. Table 10 represents the concentration of substances of environmental concerns emitted in the different unit processes of waste management in Johannesburg. The substances were selected based on a concentration of 1000 kg and above in the LCI result in this study. MRF is an environmentally beneficial waste management option as observed in Table 9. MRF emitted the lowest amount of these substances of environmental concern despite their higher concentration to other unit processes. However, a higher mass of magnesium, nitrate, and SO_2 was emitted in MRF than the WC&T. The MRF option is a favorable consideration in sustainable waste management because of its minimal environmental impact. As revealed from the table, landfills emit the highest concentration of these substances into the atmosphere. The landfill is the major emitter of substances such which contribute to global warming. It emits the highest concentration of anthropogenic gases such as carbon dioxide and methane which absorbs radiation from sunlight to increase the global atmospheric temperature. This brings about changes in the climate and other associated impacts. All the unit processes emit a high amount of anthropogenic water-soluble iron which influences aquatic habitats. Incineration and composting processes emit a higher concentration of SO_2 which affects human respiratory systems and irritates the eyes with a potential for respiratory infections. When emitted into the air, it forms a major constituent of acidic rain which degrades the quality of the ecosystem. A study by Adeyemi and Ojekunle (2021) revealed the health risk of heavy metals such as lead (Pb), cadmium (Cd), chromium (Cr), nickel (Ni), iron (Fe), zinc (Zn), copper (Cu), and manganese (Mn) which are released through anthropogenic activities. The result of the study revealed that the health hazard and the cumulative cancer risk of these heavy metals concentration in groundwater pose a risk for humans at different age groups especially children. A similar study by Ganiyu et al. (2021) revealed that lead and cadmium have a significant input in cancer risk factors. The higher concentration of methane prominently from the landfill sites with and without energy recovery can lower the level of oxygen intake. This can lead to several mild and several health consequences on humans respiratory systems such as nausea, and variation in breathing and heart rate among others. The release of dioxin during incomplete combustion of waste in the incinerator has a high negative consequence on human health due to their resistance to bio-degradation and high toxicity (Giusti 2009). The study of Kanhai et al. (2021) reported that 120 deaths can be avoided by 2030 by preventing open burning of waste which results in a 94% decline in particulate matter emissions ($PM_{2.5}$) health burden

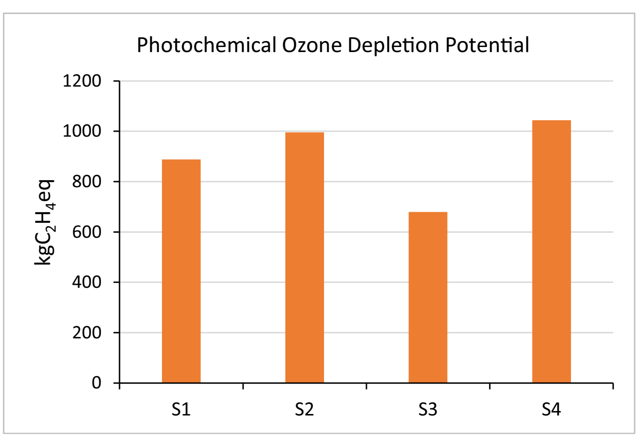

Fig. 12 Photochemical ozone depletion Potential in all scenario

According to the result of the LCA in this study, the MRF options are the most environmentally beneficial waste management options due to their lowest values in all impact categories except AP. It is therefore a reasonable consideration in sustainable waste management. Landfilling is the highest contributor to GWP and ODP thereby making scenario 1 the most impactful in terms of GWP and ODP. Incineration and composting emit substances that contribute significantly to acidification, and this is attributed to the high AP in S3 and S4. The incineration process was found to have the highest impact based on EP and PODP. It was further revealed that scenario 3 involving WC&T and incineration is the most environmentally friendly option based on GWP, ODP, and PODP owing to its lowest impact values in these impact

Table 9 Mass concentration of selected environmentally significant substances in each unit operations

Substance	Compartment	WC&T (kg)	MRF (kg)	Composting (kg)	Incineration (kg)	Landfill (kg)
Carbon dioxide (biogenic)	Air	14,714.44	1095.99	17061.81	21,550.29	23,764.42
Carbon dioxide (fossil)	Air	3073.49	1530.79	23034	30,099.63	31,570.88
Iron	Water	3234.49	2679.89	40985	52,693.86	62,783.86
Magnesium	Water	7105.78	10,390.45	158,794	204,304.53	204,304.53
Nitrate	Water	695.526	1030.80	15,504.49	19,948.29	18,431.78
Nitrogen oxides	Air	14,027.74	6831.86	104,503.55	134,332.90	126,421.90
Particulates, > 10 µm	Air	4536.39	2131.47	32,579.98	41,910.57	33,642.57
Phosphate	Water	2313.19	3460.89	52,891.89	68,050.49	78,850.65
Sodium	Water	25,784.81	11,761.04	179,790.11	231,254.15	21,467.43
Sulfur dioxide	Air	6232.37	12,294.93	187,901.28	241,751.86	36,986.65
Chemical oxygen demand (COD)	Water	8847.26	378.18	5913.14	7436.01	7687.00
Dissolved organic carbon (DOC)	Water	3403.29	267.56	4190.16	5261.02	7234.24
Methane, fossil	Air	3196.97	8.58	5917.75	7593.97	11,843.65

categories. Scenario 1 comprising WC&T and landfilling had the least impact on AP and EP. However, it had the highest impact on ODP and GWP which is attributed to the landfill's high impact on GWP and ODP. The alternative integrated waste management system in scenario 4 had the highest impact based on PODP, EP, and AP. From an environmental perspective, S4 is the least beneficial option.

Its standalone form as a unit process of waste management, the environmental impact of incineration cannot be considered better than other options like anaerobic digestion, recycling, and composting. However, when considered as an integrated waste management system for 100% waste treatment such that the landfilling of mixed waste from the city of Johannesburg is phased out, it provides a greater environmental benefit. Option S3 is a future alternative that considers the phasing out of the landfilling option through the incineration of all the waste generated in the city of Johannesburg. As revealed in this study, the phasing of landfilling option in the future alternative S3 has a greater potential of reducing the environmental impact on global warming, climatic change, and ozone depletion far beyond the trend in the current scenario. These impact categories are significant environmental issues in the city of Johannesburg. Other unit processes which are also phased out in option S3 and the attendant environmental consequences in some of the impact categories contributed to its minimum overall impact which are major drivers to its preference from an environmental perspective. Incineration has gained traction and attention globally owing to its environmentally friendly properties of evading the emission of methane, soil, and water pollution aside from its potential of reducing landfilling of mixed waste by mass and volume, heat, and energy recovery potential (Cudjoe and Acquah 2021). A favorable environment reduction in climatic change, human pollution, and acidification through the incineration of MSW was reported in China Business Park by Guo et al. (2018). Scenario S4 is also an option that considered the phasing-out of the landfilling. However, other treatment techniques considered in the integrated systems increased the overall impact of S4. A general overview of the trend of each scenario in all impact categories is represented in Table 10. This depicts the ascending order of impact of each scenario in all the impact categories.

Table 10 General overview of the trend of impact of all scenarios across all impact categories

Impact category	Order of impact			
	Lowest	Lower-medium	Upper-medium	Highest
GWP	S3	S4	S2	S1
ODP	S3	S4	S2	S1
AP	S1	S3	S2	S4
EP	S1	S3	S2	S4
PODP	S3	S1	S2	S4

Conclusion

This study evaluated the environmental impact of the present, emerging, and alternative waste management options in the city of Johannesburg, South Africa. A complete impression of the environmental performance of the unit operations which make up the waste management systems in Johanbesburg and different waste management scenarios comprising two or more unit operations was created in this study. The potential environmental benefit of phasing out the landfilling option in future scenarios was investigated. The result revealed that no scenario had the best performance in all the impact categories. However, S3 can be considered as the best option environmentally because it has the lowest impact in most of the impact categories. S3 has the lowest impact based on GWP, ODP, and PODP which are 33.19 × 10^6 $kgCO_2eq$, 0.563 kgCFC-11e and 679.46 kgC_2H_2eq respectively. Also, S4 can be regarded as the most impactful option since it has the highest contributions to PODP, AP, and GP which are 1044 kgC_2H_2eq and 892073.8 $kgSO_2eq$ respectively. In terms of GWP and ODP, S1 is the most impactful. The assessment result in this study has presented the LCA method as a viable tool that allows a holistic comparison between different waste management alternatives from an environmental perspective to support sustainable waste management decisions.

Based on the result of this study which revealed the alternative scenario S3 involving a phasing-out of landfilling of mixed waste through a 100% incineration of the waste as the most environmentally friendly option in the city of Johannesburg, a further study into the intensive investigation of the environmental impacts of the incineration process through a life cycle assessment tools is recommended. Most studies in Africa are focused on the potential of incineration for reducing the volume of waste and generating power. However, limited studies focus on the environmental assessment of the process. To achieve an effective waste treatment through incineration and a sustainable utilization of the residues of incineration for different applications as recommended in this study, an extensive study of pollutants in incineration flue gases and the state of the art technology for cleaning the gas is recommended. This will present a complete view of the environmental burden of the incineration process which will make the alternative option S3 the perfect waste management system in the city of Johannesburg. In addition, effective environmental regulatory policy for the incineration process by concerned policy makers is recommended.

It has also been observed that a two-dimensional evaluation of waste management systems involving the environmental assessment and life cycle cost assessment is more beneficial to sustainable waste management decisions. A life cycle cost assessment of the management system in Johannesburg is hereby recommended.

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Consent for publication Not applicable.

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