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Life cycle analysis of potential municipal solid wastes management scenarios in Tanzania: the case of Arusha City

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Abstract

The municipal solid wastes (MSW) management technologies in most cities of developing countries pose a continuous risk of contaminating the environment and affecting human health adversely; often because MSW technologies are not comprehensively analyzed before their implementation. For this purpose, the life cycle assessment methodology was applied to access the different MSW management scenarios in Arusha City, Tanzania. Three different scenarios of recycling and sanitary landfilling (RSL) were developed as the business as usual scenario (RSL) (SN-1), RSL combined with composting (SN-2), and RSL combined with anaerobic digestion (SN-3). Results obtained showed that no scenario performed better in all impact categories, however with the current focus on climate change and limited funds in developing countries, the best option would be SN-2. The SN-2 which is the combination of recycling, composting and the landfill had the least economic cost and environmental burdens in most categories when compared to the other scenarios. The sensitivity analysis results indicated that improving diesel consumptions, reducing methane emissions to air and increasing the recycling rate of papers and plastics would reduce the total environmental impacts on all scenarios.

Keywords: Arusha city, Economic, Environment, Impact factors, Life cycle assessment, Municipal solid wastes

Introduction

The municipal solid wastes (MSW) management in most cities of developing countries is still unsatisfactory despite several efforts to tackle it squarely. MSW management involves the collection and transport of waste, recovery of useful materials, and final disposal. These steps can lead to negative environmental impacts such as the release of greenhouse gases. For instance, by the year 2016, about 1600 Mt of carbon dioxide equivalent (CO_2-equivalent) greenhouse gas emissions were being generated from MSW annually, worldwide [1]. The life cycle assessment (LCA) tool is very crucial for evaluation and comparison of environmental burdens caused by different treatment options along with the entire life cycle treatment of the activity, process or product [2].

With the LCA tool, extensive studies on environmental impact assessment of MSW have been conducted worldwide. Khandelwal et al. [3] compared landfilling and the combinations of the different treatment options such as material recovery facility (MRF), composting, and anaerobic digestion in Nagpur city, India using LCA tool. The results of the study indicated that the combination of the MRF, landfill and composting has lower environmental impacts on most impact categories assessed compared with the other combinations of MRF with anaerobic digestion. Oyoo et al. [4] compared four different waste management scenarios in Kampala city of Uganda: open dumping and composting, landfilling, combining composting, recycling and the landfill, combining anaerobic digestion, composting, recycling and the landfill. It

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was concluded that the last one is the best for all impact categories assessed. Another study was carried out by Dong et al. [5] who compared three treatment alternatives in Hangzhou, China; landfill with energy recovery, landfill without energy recovery and incineration with the energy recovery. The best alternative concluded was incineration with energy recovery.

Therefore, different MSW technologies have been selected via the LCA tool that best suits the local conditions of the concerned area. The difference in results is due to many factors including data used, decision to include or not to include equipment which causes emissions, system boundaries considered in the analysis and local conditions of the concerned study area [6]. Also, MSW in developing countries has high organic content and lower calorific values as compared to the wastes in developing countries [7], and as such previous studies in developed countries cannot be generalized in sub-Saharan Africa where LCA studies are limited. In Tanzania specifically, the LCA applications for MSW decision making are yet to be applied and there is no single study on LCA on MSW that have been published in a peer-reviewed journal. Kazuva et al. [8] assessed the best MSW treatment options in Dar es Salaam City, Tanzania using a multi-criteria analysis approach Elimination and Choice Expressing Reality (ELECTRE). The ELECTRE decision-making tool aids the decision-makers to select best alternatives scenarios from several possible alternatives which are outranked by others in a selection [9, 10]. However, the study above [8] focused only on CO_2 emissions as an environmental factor and thus further studies are required for correct interpretation since emissions such as methane, ammonia, nitrogen oxides, particulate matter just to mention a few are also likely to be impacted by MSW. Besides, previous LCA study described above [4], that could present the similar situation in Tanzania did not focus on several impact categories such as freshwater eutrophication, particulate matter formation and freshwater ecotoxicity which are also likely to be impacted by MSW. The present study aims at comparing the environmental impacts of different waste management scenarios for Arusha City, Tanzania. In Arusha City, the waste management practices include; recycling and sanitary landfilling even though organic waste fraction comprises a higher percent (67%) which would require other options such as composting or anaerobic digestion. In our work three scenarios were analyzed which include; the business as usual scenario (BAU) of recycling and landfilling (SN-1), recycling and composting combining with landfilling (SN-2), recycling and anaerobic digestion combining with landfilling (SN-3). The environmental impact categories considered in this study include climate change, photochemical oxidant formation, freshwater eutrophication, terrestrial acidification, freshwater ecotoxicity, terrestrial ecotoxicity, human toxicity and particulate matter formation.

MSW management in the study area

Arusha city is located in the northeast of Tanzania and is divided into 25 wards of which the collection of MSW is made. In Arusha city, the private companies and the community-based organization do the collections of the MSW from 25 wards and transport the wastes at the Muriet sanitary landfill for the disposal. The Muriet landfill site is allocated about 6.5 km from the City Centre and has been in operation since January 2019. This newly constructed landfill has the provisions for the landfill gas collection and leachate collections. At the landfill, about 400 registered waste pickers do the separation and collection of the recyclable materials and sell them at nearby landfill pre-processing centers. The city generates about 271 t d^{-1} with the waste compositions of 67% organic, 11% papers, 7% plastics, 6% textiles, 4% glass, 4% ashes and 1% metals, with an average moisture content of 59.8% [11]. The high organic content suggests that biological treatment options such as composting and anaerobic digestion would be suitable for life cycle analysis in this city. Other proposed treatment facilities such as composting and anaerobic digestion are also assumed to occur at the same site.

Materials and methods

The LCA of the study was conducted as per the methodology described in ISO 14040 [12]. The ISO 14040 LCA methodology considers four main steps including; goal and scope definition, lifecycle inventory, life cycle analysis and interpretation. The ReCiPe 2008 Midpoint (H) V1.13 method was used to calculate the results because Umberto LCA software used in the analysis was using the ecoinvent version 3.6 [13] of which ReCiPe 2008 Midpoint (H) V1.13 is one of the few updated methods.

Goal and scope definition

This study aimed to analyze and compare the impacts on the environments due to MSW management scenarios through the use of the life cycle methodology in such a way that could promote the more suitable waste management option. The life cycle considered is the end of life stage of which materials becomes wastes when its values cease and therefore are collected for treatment and disposal. In the analysis, we also considered the "zero burden assumption" of which upstream environmental burdens were not included in the analysis. The functional unit considered to analyze and compare the alternative scenarios is based on one metric ton of MSW of Arusha city, Tanzania. In this study, two new proposed scenarios and existing scenario (BAU) for MSW practices of Arusha, Tanzania were analyzed and

compared. Figure 1 shows the system boundary which includes MSW, inputs of materials and energy, and outputs like air and water emissions, fertilizers (compost and digestate), electricity generated from anaerobic digestion and landfilling process. The recyclable materials are placed outside the system boundary and their emissions are excluded in the analysis. This is because they are common to all scenarios and the consumers of the recycled scraps bear the burdens of recycling activities. Based on this proposed system boundary, Table 1 depicts the summary of the scenarios studied. Scenario (SN-1): The BAU (RCL_LF) Scenario presents currently practice for the MSW management in Arusha city of Tanzania. The MSW collected in the city are transported for the disposal at Muriet Landfill whereas recyclable materials (14.2%) including paper/cardboard, metals, plastics and glass are recovered by the waste pickers and the rest of the wastes (85.8%) are landfilled. Currently, there is no operating burning unit for reducing the volume of the wastes that are landfilled. Since the Muriet landfill is nearing people residences and has approximately 400 registered waster pickers, the burning units are also excluded in the proposed alternatives since could have immediate effects on people's health.

Scenario (SN-2): This scenario (RCL_CP_LF) assumes recyclable materials (14.2%) are recovered by waste pickers as per current status, but 67% which is organic wastes are composted, and the residue wastes (18.8%) are landfilled. The composting process is assumed to be carried out in a batch-wise operation where the wastes will be placed in large piles and turning of the windrows will be accomplished through the use of the turning machines. Scenario (SN-3): This scenario (RCL_AD_LF) assumes recyclable materials (14.2%) are recovered by waste pickers as per current status, but 67% which is organic wastes is treated in the anaerobic digestion process, and 18.8% of the residue wastes are landfilled. Following Igoni et al. [14], the batch digester systems are recommended for the production of biogas from large amounts of MSW since they are very economical in terms of operations. For this economic reason in our study, we considered the anaerobic digestion process to occur in a batch process. Due to high moisture content (59.8%) of Arusha MSW, the waste incineration option was not considered.

Life cycle inventory

Inventory data related to the study were calculated through various means including; personal calculations from MSW compositions of the study area, personal communications with Marco Chacha and James Lobikoki who are responsible for MSW management of Arusha City, on-site investigations at the landfill, markets places, MSW pre-processing centers and through various published works of literature. The Umberto LCA+ software library and ecoinvent 3v6 database (Accessed from Michigan server of

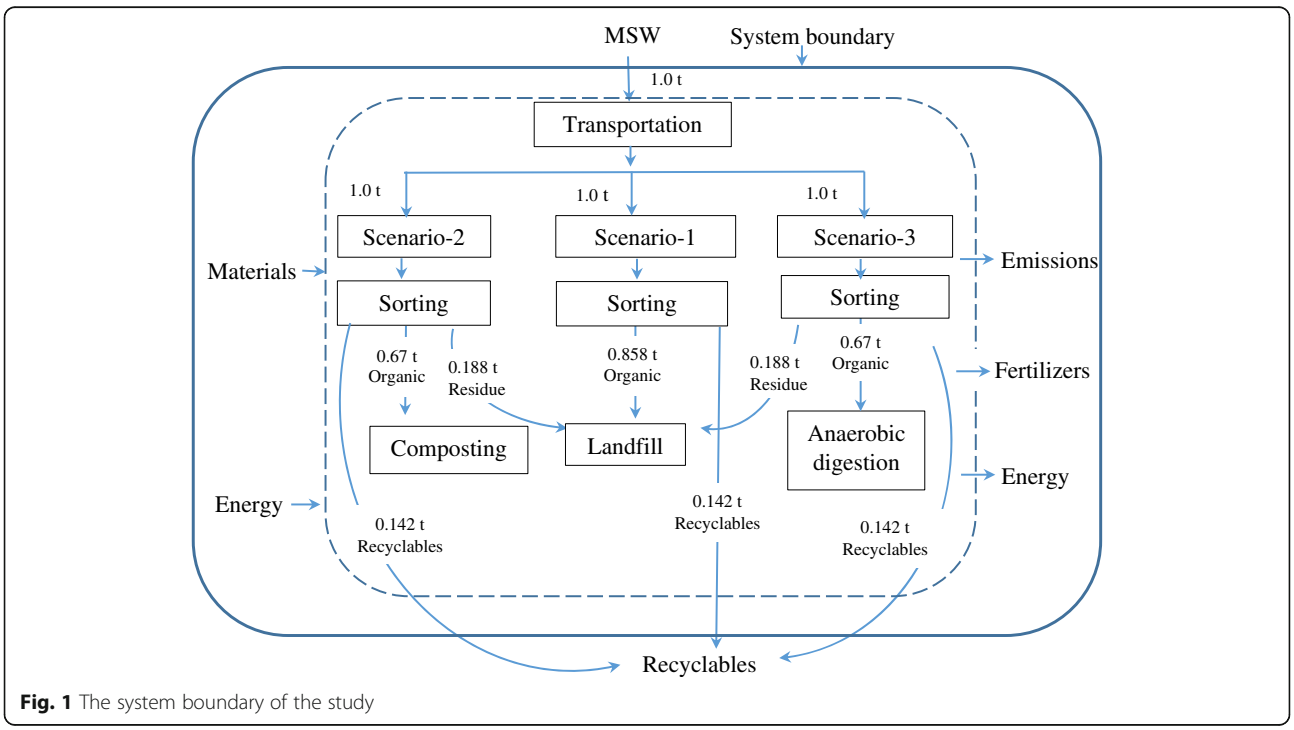

Fig. 1 The system boundary of the study

Table 1 Description of the considered scenarios for the life cycle assessment

Scenario	Description
SN-1 (BAU) (RCL_LF)	14.2% Recycled (1.6% glass, 0.8% metals, 5.5% papers, 6.3% plastics) + 85.8% Landfilling (67% organic, 8% ashes, 2.4% glass, 0.2% metals, 5.5% papers, 0.7% plastics, 2% textiles)
SN-2 (RCL_CP_LF)	14.2% Recycled (1.6% glass, 0.8% metals, 5.5% papers, 6.3% plastics) + 67% Composting (67% organic) + 18.8% Landfilling (8% ashes, 2.4% glass, 0.2% metals, 5.5% papers, 0.7% plastics, 2% textiles)
SN-3 (RCL_AD_LF)	14.2% Recycled (1.6% glass, 0.8% metals, 5.5% papers, 6.3% plastics) + 67% Anaerobic Digestion (67% organic) + 18.8% Landfilling (8% ashes, 2.4% glass, 0.2% metals, 5.5% papers, 0.7% plastics, 2% textiles)

SN Scenario, *BAU* Business, as usual, RCL: Recycling, LF: Landfilling, CP: Composting, AD: Anaerobic digestion

USA) were used to supply the rest of the information necessary for this study. Table 2 indicates the inventory data under each scenario used in this study [13, 15–20].

Waste transportation

The estimated distance per ton of the study area that is required as input to the Umberto software for the life cycle analysis is based on 7.5 t trucks (54 Nos, loaded with 5 t, return empty) transporting the wastes at about 6.5 km daily. The transport truck "Transport, freight, lorry, 3.5-7.5, metric ton" was selected from ecoinventv3 database of the Umberto LCA software.

Recycling

The recycling of the recyclables materials is expected to occur at the existing sanitary landfill. In recycling activities, the manual sorting of waste was considered instead of the material recovering facility due to the presence of the registered waste pickers in the study area. We also applied an allocation strategy in which the burdens of recycling activity are allocated to the consumers of the recycled scraps, and therefore their emissions were not included in the life cycle inventory analysis [6].

Table 2 Inventory data under each scenario per ton of MSW

Parameters	Unit	SN-1	SN-2	SN-3	Ref.
Foreground data					
Avoided products					
Electricity	kWh	43.55	–	137.3	[13, 15, 16]
Fertilizer (N)	kg	–	0.34	0.42	
Fertilizer (P)	kg	–	0.40	0.22	
Fertilizer (K)	kg	–	1.94	0.33	
Background data					
Electricity consumption	kWh	0.42	–	2.95	[17–19]
Diesel	L	2.574	0.8789	0.564	
Emissions					
Particulates, < 10 µm	g	0.75	0.75	0.20	[19]
Sulphur dioxide (SO_2)	g	0.17	0.17	2.01	
Nitrogen oxides (NOx)	g	7.44	39.40	127.30	[20]
Total Nitrogen (TN)	kg	2.85			
Total Phosphorus (TP)	kg	4.50			
Methane (CH_4)	kg	55	0.83	8.98	This study
Ammonia (NH_3)	g	3.35	1271.2	714.0	This study

SN1: Scenario 1; SN2: Scenario 2; SN3; Scenario 3

Composting

In this study, it is assumed that windrow composting will be employed. The decomposition of the organic matter and diesel requirements by the turning machines during composting process contribute to the greenhouse gas emissions. In most literature typical diesel requirements in windrow composting by turning equipment is estimated at 0.47 L t^{-1} of waste [18]. The total amount of carbon and nitrogen present in a metric ton of the compostable wastes was estimated from MSW compositions of the study area (Table 3). The total amount of carbon and nitrogen present in a wet metric ton of wastes (67% organic wastes) were calculated as 151.4 kg-C and 6.5 kg-N per wet mass respectively. Literature suggests that about 50% each of carbon and nitrogen are degraded for the production of the mature compost [16], and so we adapted the same percentage in our calculations. We computed the methane emission as 1.1% of the fraction degraded carbon during the composting process [21]. We also computed the ammonia emission as 19.5% of the total nitrogen presents in a compostable waste [22]. Other emissions were obtained from the literature. Umberto LCA+ software and ecoinvent v3.6 database were used to supply the indirect emissions of the diesel consumption by equipment during the composting process. The ReCiPe 2008 Midpoint (H) V1.13 methodology was applied to obtain their emissions. Since the biowaste of the study area comprises of 55% food wastes and 45% garden wastes, which are similar to compositions of waste as per Boldrin et al. [16],

Table 3 Moisture and major elemental composition (%) of the typical wastes in the study area [9]

Moisture	C	H	O	N	S	Cl	P
59.79	56.20	5.42	35.49	2.42	0.31	0.05	0.11

the estimates of the average value of 0.34 kg-N, 0.40 kg P and 1.94 kg-K of inorganic fertilizers are assumed to be recovered per one metric ton of MSW during the composting process. The recovered nutrients are assumed to bring the benefit of avoided production of the fertilizers. The leachates produced during the composting process are assumed to be recycled back in the process and therefore emissions in water were not considered.

Anaerobic digestion

When organic matter is degraded under anaerobic digestion it releases methane and carbon dioxide in larger percent including the lower percentages of hydrogen, hydrogen sulphide, ammonia, and siloxanes, aromatic and halogenated compounds [23]. To quantify emissions in the anaerobic digestion process we adapted the modified Buswell equation [24].

$$\begin{aligned} &C_aH_bO_cN_dS_e \\ &\quad + (a - 0.25b - 0.5c + 0.75d + 0.5e)H_2O \\ &\quad = (a + 0.125b - 0.25c - 0.375d - 0.25e)\ CH_4 \\ &\qquad + (a - 0.125b + 0.25c + 0.375d + 0.25e)CO_2 \\ &\qquad + d\ NH_3 + e\ H_2S \end{aligned} \tag{1}$$

The typical elemental composition of the Arusha MSW is shown in Table 3, and the molecular equation was calculated from dividing the elemental compositions and atomic weights of the elements. Hence, for one metric ton of the waste to be digested, the biodegradable waste would be about 670 kg (67%). It contained C: 376.5 kg, H: 36.3 kg, O: 237.8 kg, N: 16.2 kg, and S: 2.1 kg and the molecular equation for emission were obtained as;

$$\begin{aligned} C_{31.4}H_{36.3}O_{14.9}N_{1.2}S_{0.1} + 15.82\ H_2O &\rightarrow 16.04\ CH_4 \\ &+15.36\ CO_2 + 1.2\ NH_3 \\ &+0.1\ H_2S \end{aligned}$$

From the molecular equation and the computation, about 257 kg CH_4 and 676 kg CO_2 were obtained and since the complete digestion depends on many factors, hence the complete digestion may not be achieved, the proportionality factor of 0.7 was used to adjust the value and hence about (180 CH_4 kg and 473 kg CO_2) are obtained. We assumed that 5% (9.0 kg) of methane is not captured for electricity generation and hence contributing to the emissions in the environment as per Belboom et al. [25]. Kaza and Bhada-Tata [15] indicated an electrical potential recovery per ton of MSW in anaerobic digestion to be in the range of 165–245 kWh. In this study, we adapted an average value of 205 kWh and electricity consumption of 4.4 kWh per metric ton of MSW. With the current under-construction Rufiji hydroelectric power in Tanzania which has the capacity of 2115 MW, the main source of energy in Tanzania considered in the analysis is hydro-electric power [26]. Electricity consumption in the anaerobic digestion process is due to refining the waste ready for the digestion process. From ecoinvent database of Umberto software used, the application of the digestate for fertiliser use provides the nutrients of; N:0.629%, P_2O_5:0.331% and K_2O: 0.495% per kg of fresh digestate. Therefore, with the assumption that processing one metric ton of organic matter in anaerobic digestion process generates about 100 kg of digestate [3], about 0.42 kg-N, 0.22 kg P and 0.33 kg-K are assumed to be recovered per one metric ton of MSW during the digestion process.

Landfill

Emissions in a landfill can be attributed by the degradation of the organic matter as well as diesel requirements by vehicles used in the compaction of the wastes. To quantify the amounts of methane and carbon dioxide, we adapted the generalized equation bellow [18]:

$$\begin{aligned} &CH_4\text{emissions}\ (\text{kg t}^{-1}\text{of MSW}) \\ &\quad = MSW_L{*}MCF{*}DOC{*}DOC_F{*}F{*}(16/12 - R){*}(1 - OX) \end{aligned} \tag{3}$$

where MSW_L is the wet weight of the MSW disposed at the landfill. The MCF refers to the methane correction factor and ranges between 0.4 and 1 for unmanaged and managed well landfills [27]. We adapted the average values of 0.7, because in most developing countries the landfills may not be perfectly managed. DOC is the percentage of the degradable organic carbon in wet waste and DOC_F is the fraction of the degradable carbon that converts to the landfill gas through waste decomposition. In the study area, the DOC of the landfilled waste comprises of food waste 37%, garden and wood 30%, and papers 11% (Landfilled 5.5%). By considering the typical composition of each organic wastes to be landfilled and estimated DOC_F for waste component (Food waste = 0.64, wood waste = 0.21 and papers = 0.37) as measured by Biochemical *methane* potential test [27], the DOC_F of the waste composition in the study area was estimated at 0.41. The value 16/12 is the carbon content of methane, F refers to the methane concentration in landfill gas, R is the recovered methane fraction and OX is methane oxidation factor and were estimated as F = 50%, R = 50%, OX = 36%) [28]. From the computation, about 55 kg CH_4 are estimated as emissions to the environment. During the compaction process of the wastes in a landfill, about 3 L of diesel fuel t^{-1} of MSW are utilized [29]. To process one metric ton of MSW in

a landfill an electricity consumption of 0.42 kWh t^{-1} of MSW would be required of which electrical potential recovery is estimated at 65 kWh t^{-1} of MSW [15, 17]. Inventory data and their associated emissions due to recyclable materials such as scrap metals, glass, plastic wastes that are landfilled were obtained from ecoinvent v3.6 database embedded in Umberto LCA software. As the study adopted the same percentages of 18.8% of the recyclables materials that are landfilled in all scenarios, the impacts of their emissions are the same in all scenarios.

Life cycle impact assessment (LCIA)

The LCA methods (The ReCiPe 2008 Midpoint (H) V1.13) and Umberto LCA+ software were used to evaluate the impact categories. The impact categories selected were climate changes, photochemical oxidant formation, freshwater eutrophication, terrestrial acidification, freshwater ecotoxicity, terrestrial ecotoxicity, human toxicity and particulate matter formation. These impact categories were selected because the groundwater and surface water are the main sources of water in Arusha City and therefore emissions from the proposed MSW treatment might be detrimental to water sources, land and air.

Sensitivity analysis

The sensitivity analysis focused on assessing whether improvement on the process which mostly contributed to impact categories would result in an improvement on impact categories. This was achieved through assuming an increase of 5% improvement on different process and recovery of the resources in scenarios, and then the variability (in terms of range) upon improvement was determined. Another sensitivity analysis performed aimed at evaluating the reliability of the ReCiPe 2008 Midpoint (H) V1.13 LCIA results obtained. This was achieved by comparing the LCIA results obtained from ReCiPe 2008 Midpoint (H). V1.13 with the results obtained from intergovernmental panel on climate change (IPCC 2013) and international life cycle data system (ILCD 2.02018) LCIA methodologies [30, 31].

Results and discussion

Environmental impacts of systems without resources recovery

Table 4 depicts the environmental impact of each scenario without the electricity and compost recovery. SN-1 showed high environmental impacts on most categories except for the human toxicity, particulate matter formation and terrestrial acidification. The high environmental impacts on SN-1 could be attributed by direct methane emissions and diesel consumptions during the compaction process. The decomposition of the biodegradable wastes produces emissions in all scenarios. Most of the methane generated in a landfill is not captured resulting in high climate change and photochemical oxidant formation in SN-1 than in composting (SN-2) and anaerobic digestion (SN-3). Similar observations were indicated by Maalouf and El-Fadel [32], who indicated that methane emissions in a landfill are the major contributor for climate change and photochemical oxidant formation. Thus, diverting the organic waste fractions to composting or anaerobic digestion process would significantly reduce the climate change and photochemical oxidant formation. SN-1 has also a higher terrestrial ecotoxicity in a comparison with other scenarios due to higher diesel consumptions since all wastes are assumed to be compacted during the landfilling process. Whereas in SN-2 and SN-3 wastewater emissions were not considered, but SN-1 resulted in higher freshwater eutrophication due to total nitrogen and total phosphorus nutrients emissions. Landfilling of papers and plastics was the dominant factor for human toxicity and freshwater ecotoxicity in all scenarios. Since the same amount of papers and plastics is assumed to be landfilled in all scenarios, there are slight differences in impact categories of human toxicity and freshwater ecotoxicity among scenarios. For composting (SN-2) ammonia emission was a dominant factor for particulate matter formation and terrestrial acidification impact categories. The large fraction of the nitrogen is lost as ammonia during the composting process causing high ammonia emission in composting (SN-2) than in landfill (SN-1) and AD (SN-3) [22]. The literature points out that environmental emission minimization in a composting process can be achieved through properly blending of the feedstock to achieve the required carbon to nitrogen ratio of 20–40 for fast composting, use of the odor removal devices, and promotion of home composting to minimize emissions due to transport process [4, 22]. Besides landfilling of paper and plastics in SN-3, electricity consumptions, ammonia and methane emissions were the dominant factors for freshwater eutrophication, particulate matter formation, and climate change, respectively. In anaerobic digestion (SN-3) high amount of methane is generated but the high percentage is captured for an electricity generation [25]. The methane generation in composting (SN-2) is very low as compared to the landfill (SN-1), and anaerobic digestion (SN-3) in a such a way that some pieces of literature assume no CH_4 is emitted during the composting process [16].

Figure 2 indicates the percentage of contributions of the major substances to the impact categories. Results showed that for freshwater eutrophication, phosphorus was a dominant contributor for SN-1, phosphate for SN-2 and electricity for SN-3. For the all scenarios Manganese contributed most to human toxicity. For particulate

Table 4 Environmental impacts of systems without resources recovery

Category	Unit	SN-1 (RCL_LF)		SN-2 (RCL_CP_LF)		SN-3 (RCL_AD_LF)	
		Value	Process	Value	Process	Value	Process
Fresh water eutrophication	kg P eq	4.5	Nutrients (99%)	6.4×10^{-4}	Phosphate (81%)	1.7×10^{-3}	Electricity (64%)
					Diesel (18%)		Phosphate (28%)
Human toxicity	kg1,4-DCB eq	10.9	LF of papers (69%)	10.5	LF of papers (71%)	11.2	LF of papers (67%)
			LF of plastics (21%)		LF of plastics (22%)		LF of plastics (21%)
Particulate matter formation	kg PM_{10}	0.05	Diesel (80%)	0.44	NH_3 (93%)	0.28	NH_3 (82%).
Fresh water ecotoxicity	kg 1,4-DCB eq	0.86	LF of papers (46.5%)	0.83	LF of papers (48%)	0.86	LF of papers (46%)
			LF of plastics (43.0%)		LF of plastics (45%)		LF of plastics (43%)
Climate change	kg CO_2 eq	1305	CH_4 emission (94%)	91	CH_4 emission (93%)	274	CH_4 emission (97%)
Terrestrial ecotoxicity	kg 1,4-DCB eq	1.1×10^{-3}	Diesel 35%)	8.7×10^{-4}	Transport (36%)	8.9×10^{-4}	Transport (35%)
			Transport (27%) LF of plastics (24%)		LF of plastics (32%)		LF of plastics (31%)
Photochemical oxidant formation	kg NMVOC eq	0.74	CH_4 (76%)	0.14	Diesel (28.5%)	0.3	NO_2 (43%)
			Diesel (18%)		NO_2 (28.5%)		CH_4 emission (40%)
					CH_4 emission (21.4%)		Diesel (10%)
Terrestrial acidification	kg SO_2 eq	0.11	Diesel (64%)	3.18	NH_3 emission (98%)	1.86	NH_3 emission (94%)

SN Scenario, *RCL* Recycling, *LF* Landfilling, *CP* Composting, *AD* Anaerobic digestion, *DCB* Dichlorobenzene, *NMVOC* Non-methane volatile organic compounds

matter formation and terrestrial acidification, ammonia was the dominant factor for SN-2 and SN-3, while diesel was a dominant factor for SN-1. For all scenarios, copper was the dominant contributor to freshwater ecotoxicity. In climate change, methane was the main contributor to all scenarios. In terrestrial ecotoxicity, diesel was the main contributor for SN-2 and SN-3. In photochemical oxidant formation, methane contributed most in SN-1, whereas nitrogen oxides contributed most in SN-2 and SN-3.

Impact of the resource recovery

Tables 5 and 6 depict the environmental impacts for producing hydropower electricity and mineral fertilizer computed from ecoinvent v.3.6 of the Umberto software. The avoided environmental burdens were subtracted from the total environmental burdens without resource recovery and their results are shown in Table 7. Results indicated that incorporating resources recovery resulted in improved environmental burdens, although it did not alter the ranking of categories in most impact categories. In anaerobic digestion (SN-3), the digestate recovery when compared with the recovery of electricity contributed to most impact categories except for freshwater ecotoxicity and climate change of which electricity was the main factor. The lower contribution by electricity recovery in SN-3 is attributed to the fact that the hydro-based power source considered in the analysis in comparisons to other power sources, has lower environmental emissions [33]. The avoided emissions resulting from producing chemical fertilizers (N, P_2O_5, and K_2O) as a result of composting and digestate recovery in SN-2 and SN-3 affected mostly human toxicity impact making SN-3 much better than SN-1, whereas SN-2 remained the most favored scenario in this category. Further comparisons of the economic estimates of each scenario were made based on the economic costs given in Table 8 [7]. From the computation, the Scenario SN-2 was found to have a low economic cost of 47 USD t^{-1}, followed by Scenario SN-1(54 USD t^{-1}) and SN-4 (70 USD t^{-1}). The scenario SN-3 had the high economic cost of 93 USD t^{-1}.

Sensitivity analysis

Sensitivity to processes improvement

The sensitivity results indicated in Table 9 show that reducing methane emissions to the environment brought environmental benefits in all scenarios of which SN-1 was highly impacted. The impacted categories were climate changes in all scenarios, photochemical oxidant

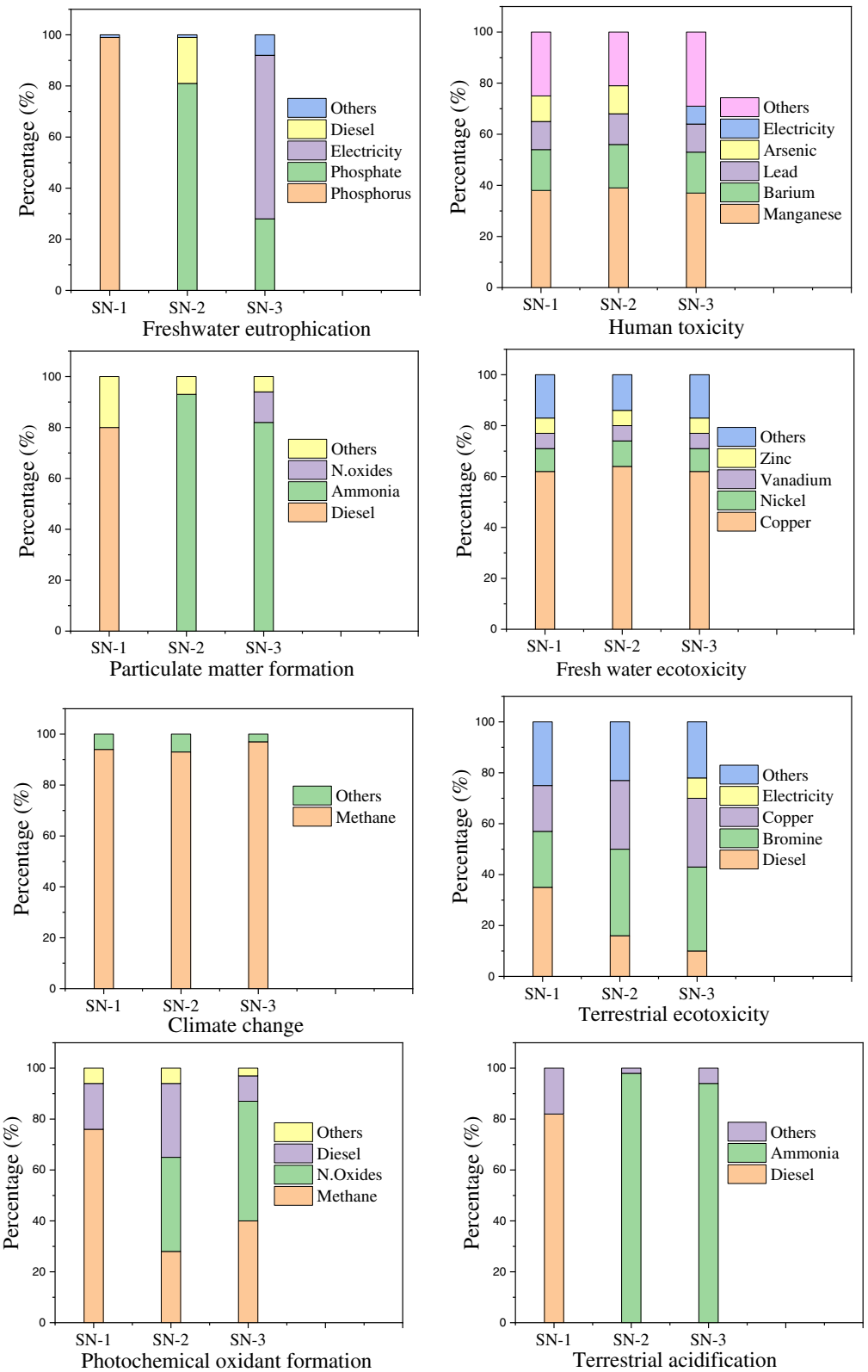

Fig. 2 Percentage contributions of the major substances to the impact categories

Table 5 Environmental impacts from the production of hydropower electricity (Ecoinvent v.3.6 database)

Category	Unit	Value		
		1 kWh*	43.55 kWh*	135.35 kWh[a]
			SN-1 (RCL_LF)	SN-3 (RCL_AD_LF)
Fresh water eutrophication	kg P eq	1.6×10^{-6}	6.8×10^{-5}	2.1×10^{-4}
Human toxicity	kg1,4-DCB eq	2.1×10^{-3}	0.09	0.28
Particulate matter formation	kg PM_{10}	2.1×10^{-5}	9.0×10^{-4}	2.8×10^{-3}
Fresh water ecotoxicity	kg 1,4-DCB eq	1.8×10^{-4}	8.0×10^{-3}	0.03
Climate change	kg CO_2 eq	0.06	2.83	8.91
Terrestrial ecotoxicity	kg 1,4-DCB eq	5.3×10^{-7}	2.3×10^{-5}	7.3×10^{-5}
Photochemical oxidant formation	kg NMVOC eq	3.8×10^{-5}	1.7×10^{-3}	5.2×10^{-3}
Terrestrial acidification	kg SO_2 eq	2.1×10^{-5}	9.2×10^{-4}	2.9×10^{-3}

SN Scenario, *RCL* Recycling, *LF* Landfilling, *CP* Composting, *AD* Anaerobic digestion, *DCB* Dichlorobenzene, *NMVOC* Non-methane volatile organic compounds
[a] Quantity of hydropower electricity contributing to the environmental impacts

formation in SN-1 and SN-3 and terrestrial acidification in SN-1. Improving electricity consumption efficiency had the highest environmental impact benefits in SN-3 and impacted on impact categories of freshwater eutrophication, human toxicity, climate change and terrestrial ecotoxicity. In SN-1 efficiency of electricity, consumptions brought some environmental benefits only in climate change and had no impact on SN-2. Reducing ammonia emissions had lower impacts in most categories except for the particulate matter formation and terrestrial acidification in SN-2 and SN-3. Improving recycling of paper and plastics exhibited higher environmental impacts in most categories of all the scenarios except for the particulate matter formation, photochemical oxidant formation and terrestrial acidification. Improvement on diesel consumption had a high impact on SN-1 in most categories except for freshwater eutrophication, particulate matter formation and freshwater

Table 6 Environmental impacts from the production of mineral fertilizers options (Ecoinvent v.3.6 database)

Category	Unit		Value			Total
			Fertilizer (Nitrogen)	Fertilizer (Phosphate)	Fertilizer (Potassium)	
Fresh water eutrophication	kg P eq	SN-2	5.1×10^{-4}	7.8×10^{-4}	1.2×10^{-4}	1.4×10^{-3}
		SN-3	6.3×10^{-4}	4.3×10^{-4}	2.0×10^{-5}	1.1×10^{-3}
Human toxicity	kg1,4-DCB eq	SN-2	0.99	0.54	0.19	1.7
		SN-3	1.2	0.3	0.03	1.6
Particulate matter formation	kg PM_{10}	SN-2	4.9×10^{-3}	3.7×10^{-3}	1.4×10^{-3}	1.0×10^{-2}
		SN-3	6.1×10^{-3}	2.0×10^{-3}	2.4×10^{-4}	8.4×10^{-3}
Fresh water ecotoxicity	kg 1,4-DCB eq	SN-2	0.15	0.07	0.02	2.4×10^{-1}
		SN-3	0.18	0.04	3.02×10^{-3}	2.2×10^{-1}
Climate change	kg CO_2 eq	SN-2	3.6	0.7	0.68	5.0
		SN-3	4.5	0.38	0.12	5.0
Terrestrial ecotoxicity	kg 1,4-DCB eq	SN-2	2.8×10^{-4}	2.8×10^{-4}	1.2×10^{-4}	6.8×10^{-4}
		SN-3	3.5×10^{-4}	1.5×10^{-4}	2.1×10^{-5}	5.2×10^{-4}
Photochemical oxidant formation	kg NMVOC eq	SN-2	9.0×10^{-3}	3.2×10^{-3}	3.3×10^{-3}	1.5×10^{-2}
		SN-3	0.01	1.7×10^{-3}	5.6×10^{-4}	1.2×10^{-2}
Terrestrial acidification	kg SO_2 eq	SN-2	0.02	7.7×10^{-3}	3.6×10^{-3}	3.1×10^{-2}
		SN-3	0.02	4.2×10^{-3}	6.1×10^{-4}	2.5×10^{-2}

SN-2; (RCL_CP_LF) and SN-3; (RCL_AD_LF), where *RCL* Recycling, *LF* Landfilling, *CP* Composting, *AD* Anaerobic digestion, *DCB* Dichlorobenzene, *NMVOC* Non-methane volatile organic compounds

Table 7 Environmental impacts results with resources recovery

Category	Unit	SN-1 (RCL_LF)	SN-2 (RCL_CP_LF)	SN-3 (RCL_AD_LF)
		Value		
Fresh water eutrophication	kg P eq	4.5	-7.7×10^{-4}	3.7×10^{-4}
Human toxicity	kg1,4-DCB eq	11	8.7	9.3
Particulate matter formation	kg PM_{10}	0.049	0.43	0.27
Fresh water ecotoxicity	kg 1,4-DCB eq	0.85	0.59	0.61
Climate change	kg CO_2 eq	1303	86	260
Terrestrial ecotoxicity	kg 1,4-DCB eq	1.1×10^{-3}	1.9×10^{-4}	2.9×10^{-4}
Photochemical oxidant formation	kg NMVOC eq	0.74	0.13	0.28
Terrestrial acidification	kg SO_2 eq	0.11	3.2	1.8

SN Scenario, *RCL* Recycling, *LF* Landfilling, *CP* Composting, *AD* Anaerobic digestion, *DCB* Dichlorobenzene, *NMVOC* Non-methane volatile organic compounds

Table 8 The average economic cost of MSW treatment options (USD t^{-1}) [7]

Treatment option	Organic waste	Plastic	Paper	Glass	Others
Recycling	–	93.9	−67	20.1	–
Landfill	58.3	71.1	67.3	70.3	68.3
Composting	47	–	–	–	–
Anaerobic digestion	115.3	–	–	–	–

ecotoxicity. In SN-2 and SN-3 the improvement on diesel consumptions had an impact on climate change, terrestrial ecotoxicity, freshwater eutrophication (only SN-2) and human toxicity (only SN-3). Generally, we can observe that improving diesel consumptions, reducing methane emissions to air and increasing recycling rate of papers and plastics are the main factors that would impact all scenarios.

Table 9 Sensitivity analysis on 5% improvement of process and resources recoveries

Categories	Unit		Electricity	CH_4	Diesel	Paper	Plastic	NH_3
Freshwater eutrophication	kg P eq	SN-1	–	–	–	–	–	–
		SN-2	–	–	6×10^{-6}	2×10^{-5}	1×10^{-6}	–
		SN-3	5×10^{-5}	–	–	2×10^{-5}	–	–
Human toxicity	kg1,4-DCB eq	SN-1	–	–	0.02	0.41	0.11	–
		SN-2	–	–	–	0.4	0.11	–
		SN-3	0.04	–	0.01	0.41	0.12	–
Particulate matter formation	kg PM_{10}	SN-1	–	–	–	–	–	–
		SN-2	–	–	–	–	–	0.02
		SN-3	–	–	–	–	–	0.01
Freshwater ecotoxicity	kg 1,4-DCB eq	SN-1	–	–	–	0.02	0.02	–
		SN-2	–	–	–	0.02	0.02	–
		SN-3	–	–	–	0.02	0.02	–
Climate change	kg CO_2 eq	SN-1	0.02	61	0.49	3.7	0.03	–
		SN-2	–	0.93	0.18	3.7	0.03	–
		SN-3	0.1	10	0.1	3.7	0.03	–
Terrestrial ecotoxicity	kg 1,4-DCB eq	SN-1	–	–	2×10^{-5}	1×10^{-5}	1×10^{-5}	–
		SN-2	–	–	8×10^{-6}	6×10^{-6}	1.4×10^{-5}	–
		SN-3	3×10^{-6}	–	4×10^{-6}	6×10^{-6}	1.4×10^{-5}	–
Photochemical oxidant formation	kg NMVOC eq	SN-1	–	0.03	0.01	–	–	–
		SN-2	–	–	–	–	–	–
		SN-3	–	0.01	–	–	–	–
Terrestrial acidification	kg SO_2 eq	SN-1	–	0.01	0.01	–	–	–
		SN-2	–	–	–	–	–	0.16
		SN-3	–	–	–	–	–	0.08

SN-1; RCL_LF, SN-2; (RCL_CP_LF) and SN-3; (RCL_AD_LF), where *RCL* Recycling, *LF* Landfilling, *CP* Composting, *AD* Anaerobic digestion, *DCB* Dichlorobenzene, *NMVOC* Non-methane volatile organic compounds

Sensitivity to LCIA methods

ILCD 2.02018 midpoint and IPCC 2013 impact methods were used for the comparison of the results obtained in ReCiPe 2008 Midpoint (H) V1.13 as indicated in Table 10. The results of ILCD 2.02018 midpoint and IPCC 2013 were similar to those of ReCiPe in the photochemical oxidant formation, and freshwater eutrophication. For the climate change, the LCIA results obtained from ILCD 2.02018 midpoint and IPCC 2013 were higher than those from ReCiPe. The difference in results could be attributed by the fact that the ILCD adapted the IPCC 2013 model with the carbon feedbacks of which the methane's 100-yr global warming potential is 34, the IPCC 2013 method in ecoinvent V3.6 of Umberto software database has the methane's 100-yr potential of 28 (with no carbon adjustment) and with ReCiPe method, it considers the methane's 100-yr global warming potential to be 22 [34]. For freshwater ecotoxicity and terrestrial acidification, it was difficult to compare LCIA results obtained from ReCiPe to those of ILCD 2.02018 because of the units used and the failure to obtain their conversion factors. Other factors such as human toxicity, particulate matter formation, and terrestrial ecotoxicity were not compared because in ILCD 2.02018 and IPCC 2013 are not quantified. Another limitation on assessing the impact methods was due to the licence limitation of the Umberto software that had only a few updated LCIA methods from ecoinvent database version 3.6. Based on the comparisons made between ReCiPe, ILCD 2.02018 and IPCC 2013 methods, the ReCiPe was consistent for photochemical oxidant formation and freshwater eutrophication.

Conclusions

This study analyzed the environmental impacts of MSW management scenarios in Arusha city of Tanzania. When the resources recovery is considered, the BAU scenario SN-1 which is the combination of the recycling and landfill leads to the most adverse environmental burdens in most categories analyzed except for particulate matter formation and terrestrial acidification. When SN-2 and SN-3 are compared upon resources recovery, the SN-2 which is the combination of the recycling, composting and landfill performed better in most impact

Table 10 Compared ReCiPe 2008 Midpoint (H) V1.13 results with other LCIA methods without resources recovery

Category	Unit		ReCiPe	ILCD	IPCC 2013
Fresh water eutrophication	kg P eq	SN-1	4.5	4.5	–
		SN-2	6.4×10^{-4}	6.4×10^{-4}	–
		SN-3	1.7×10^{-3}	1.7×10^{-3}	–
Human toxicity	kg1,4-DCB eq	SN-1	10.9	–	–
		SN-2	10.5	–	–
		SN-3	11.2	–	–
Particulate matter formation	kg PM_{10}	SN-1	0.05	–	–
		SN-2	0.44	–	–
		SN-3	0.28	–	–
Fresh water ecotoxicity	kg 1,4-DCB eq	SN-1	0.86	6.2 CTU	–
		SN-2	0.83	4.7 CTU	–
		SN-3	0.86	5.0 CTU	–
Climate change	kg CO_2 eq	SN-1	1305	1984	1665
		SN-2	91	136	115
		SN-3	274	414	348
Terrestrial ecotoxicity	kg 1,4-DCB eq	SN-1	1.1×10^{-3}	–	–
		SN-2	8.7×10^{-4}	–	–
		SN-3	8.9×10^{-4}	–	–
Photochemical oxidant formation	kg NMVOC eq	SN-1	0.74	0.74	–
		SN-2	0.14	0.14	–
		SN-3	0.3	0.3	–
Terrestrial acidification	kg SO_2 eq	SN-1	0.11	0.14 mol H^+ eq	–
		SN-2	3.3	3.9 mol H^+ eq	–
		SN-3	1.9	2.3 mol H^+ eq	–

SN-1 RCL_LF, SN-2; (RCL_CP_LF) and SN-3; (RCL_AD_LF), where *RCL* Recycling, *LF* Landfilling, *CP* Composting, *AD* Anaerobic digestion, *DCB* Dichlorobenzene, *NMVOC* Non-methane volatile organic compounds, *CTU* Comparative Toxic Units

assessment except for particulate matter and terrestrial acidifications. Further comparisons in economic cost reveal that SN-2 would be more preferable than all scenarios. Therefore, although the final choice of the best scenario would depend on assigned weights in impact categories, in developing countries where there are lack of funds and recent attention by the public on climate change, the SN-2 would be the best option among all the scenarios evaluated.

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Competing interests
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