Islam and Moniruzzaman *Sustainable Environment Research* (2019) 29:14
https://doi.org/10.1186/s42834-019-0013-8

Sustainable Environment Research

RESEARCH

Open Access

Simulation of sustainable solid waste management system in Khulna city

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Abstract

Municipal solid waste management (MSWM) is the major environmental concern for Khulna, the third largest city of Bangladesh. The aim of the study was to determine the most environmentally friendly option of MSWM system for Khulna city. The present system of MSWM in Khulna city was chosen as the baseline scenario in which recycling, composting and landfilling are 9.1, 4.4 and 86.5% respectively of the total managed waste. Different scenarios were developed by varying the percentage of recycling, composting and landfilling. The life cycle inventory analysis of MSWM system was done by integrated waste management model for each scenario. The model outputs of each scenario were classified into impact categories: emission of the following pollutants: greenhouse gases, acidic gases, smog precursors, heavy metal and organics to air and to water as well as quantity of residual waste and energy consumption or recovery. In the context of the aforesaid impact categories, scenario 7 consist of 71% composting, 13.6% recycling and 15.4% landfilling is the most favorable alternative for Khulna city.

Keywords: Municipal solid waste, Life cycle assesment, Greenhouse gases, Energy consumption

Introduction

Sustainable management of municipal solid waste (MSW) is a critical issue of the municipal authority in most of the cities in the world because of the growing volume of waste and the presence of harmful chemicals and additives in different waste fractions [1–3]. In Bangladesh, MSW management (MSWM) system is not well-organized and generally based on collection and dumping of MSW [4]. In Khulna city, the quantity of total generated MSW is 420 to 520 t d^{-1} and the Khulna city corporation (KCC) authority is responsible for waste management [5]. By door to door collection system, MSW are generally deposited in secondary disposal sites (SDS) either by the dwellers themselves or community based organizations or non-government organizations [6]. KCC performs MSWM through transportation of MSW from SDS to the final disposal sites (FDS) at Rajbandh, about 7 km away from the main city [7]. The existing practice of MSWM has led to various emissions of greenhouse gases (GHG) such as carbon dioxide from the production of new materials and methane from the decomposition of organic waste in landfills [8]. Similarly, uncontrolled disposal of MSW is a latent reason for water pollution, public health problems, explosion and landslide.

The Waste Framework Directive does not state which assessment method should be used if deviating from the waste hierarchy, but one of the possibilities is life cycle assessment (LCA), which starts as an assessment method for products but has, since the early 1990s, begun to be used on waste management as well [9]. Also LCA is an effective decision supporting tool associated with a product, process or service from cradle to grave and from production of the raw materials to final disposal of wastes for assessing different approaches of waste management through examining environmental impacts [10–13]. In Khulna city, a few studies have been found to assess the sustainable MSWM by applying LCA methodology. The aim of the present study is to determine the sustainable solid waste management system emphasizing on recycling and composting for Khulna city through LCA.

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Materials and methods

Study area

In Bangladesh, Khulna is situated below the tropic of cancer, around the intersection of latitude 22.49° N and longitude 89.34° E. Being the third largest city of country, the encompassing city has an estimated population of 1.5 million. The city has 31 wards, an estimated total land area of 47 km^2, and the population density of 67,994 km^{-2} [5]. The whole city area was selected for the survey area. There is a separate department for the MSWM in KCC namely conservancy department. The location of study area in context of Bangladesh as shown in Fig. 1.

Survey in study area

A series of field surveys were done to find the amount of MSW used for landfilling, composting and recycling. The field surveys were conducted at each location of SDS, large hauled container points (LHCP), small hauled container points (SHCP), and distinct collection routes (DCR) throughout the city. Countless questionnaire surveys were done with the drivers of waste collection vehicles, employees of conservancy department of KCC, workers of waste collection vehicles and landfill management to collect the quantity of fuel used in collection and transportation of MSW. It is to be noted that the three major seasons are winter season (December to February), summer season (March to May) and rainy season (June to September) in Bangladesh. For the simplicity of research, the year was sub-divided into the two season, i.e., dry season (October to March) and wet season (April to September). Moreover, the amount of MSW from each location of SDS, LHCP, SHCP and DCR was recorded throughout the entire November 2016 for the dry season and throughout the entire July 2017 for the wet season.

Life cycle inventory analysis

The life cycle inventory analysis was done by an integrated waste management (IWM)-2.0 model which is an Excel TM model with a visual basic graphical interface [14]. In Europe, South America and Asia, the IWM model is designed as a decision supporting tool to decide between various options for waste management in industry as well as local government [15–18].

The major input values of the model were composition of MSW, amount of recycled MSW, amount of composted MSW, amount of landfilled MSW, average driven

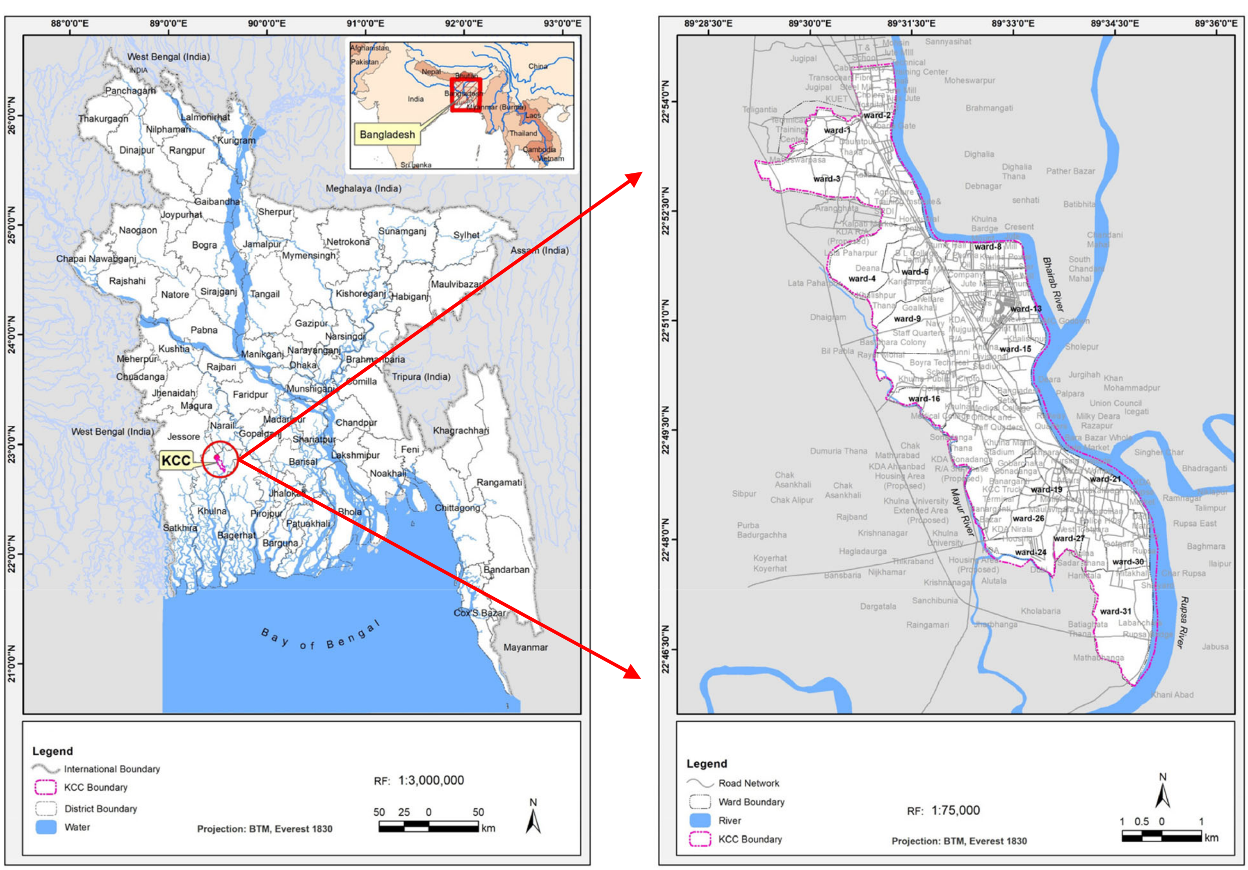

Fig. 1 Location of study area in context of Bangladesh

distance by collection and transportation vehicles, and quantity of fuel consumption. The flow diagram for life cycle inventory analysis is given in Fig. 2. The total quantity of waste collected at the curb (recyclables, organics and garbage) and the composition of the total waste stream were entered in input screen A of the model. In case of input screen B, the waste flow data such as quantity of waste sent for recycling, composting, land application, energy recovery and landfilling were entered. The data related to the collection and transportation of waste in the system such as distance driven by collection trucks, type of fuel used and fuel efficiency were entered in input screen C. In input screen D, users have the option of choosing the mix of power generation methods, or the average mix of power generation methods. Alternatively, a user can specify a custom grid by selecting the 'custom' option on screen D. 'Custom' button was selected and allowed the user to input the percentage of power generated by each of the generating methods. Input screen E will only appear if the user has entered a number greater than zero for quantity of waste recycled. The data related to recovery rates was entered on this screen. The data related to energy consumption, percent residue, residue management, distance to markets and distance from material recovery facility to landfill were entered in input screen F. The entered data on input screen G includes breakdown in tons of the materials sent for composting, composition of yard waste, energy consumption and distance from composting facility to landfill. Input screen H will only appear if the user has entered a number greater than zero for quantity of waste land applied in input screen B. The entered data in this screen were the composition of yard waste and energy consumption. The energy recovered and energy recovery efficiency were entered in input screen I. In input screen J, the data related to gas recovery, energy recovery, annual precipitation and energy consumption were entered. All the data were entered in input screen A to J for each modelled scenario. Due to the space constraint, only the entered data in baseline scenario are shown in Table 1.

The outputs of each scenario were calculated by using IWM model and classified into impact categories: emission of GHGs, emission of acid gases, emission of smog precursors, emission of heavy metal and organics to air, emission of heavy metal and organics to water, quantity of residual waste and energy consumption or recovery. The percent reduction of emission in aforementioned categories compared to baseline scenario was calculated by Eq. (1) as follows:

$$ER(\%) = \frac{EB - EM}{EB} * 100 \qquad (1)$$

where, ER = Emission reduction, EB = Emission of baseline scenario and EM = Emission of modelled scenario.

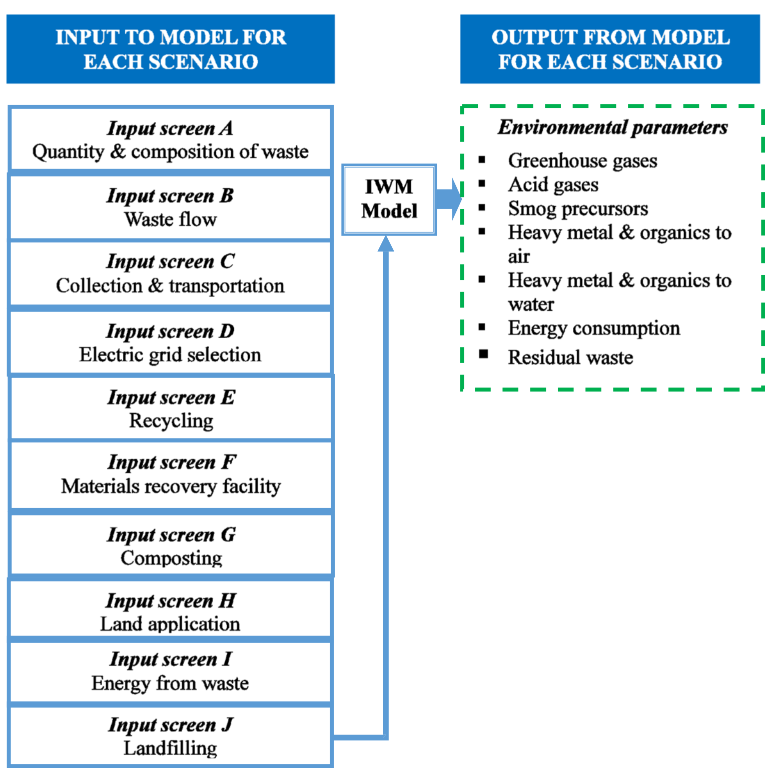

Fig. 2 Flow diagram for life cycle inventory analysis

Table 1 Details of input data for baseline scenario in IWM model

Particulars in input screens		Input data
Total quantity of managed MSW, t	Recycled MSW	37.2
	Composted MSW	18
	Landfilled MSW	356
Composition of MSW, %	Paper	9.5
	Glass	0.5
	Ferrous metal	1.0
	Aluminum	0.1
	PET	0.3
	HDPE	0.3
	LLDPE	0.5
	PP	0.3
	PS	0.3
	PVC	1.5
	Food waste	70
	Yard waste	8.9
	Other waste	6.8
Distance driven by collection truck, km	Garbage truck	2162.3
	Recycling truck	239.5
	Yard waste truck	234.3
Diesel fuel efficiency, km L^{-1}	Collection truck	2.25
	Transportation truck	2.5
Electric grid selection, %	Coal	0
	Natural gas	0
	Diesel and light fuel oil	75
	Heavy fuel oil	25
	Hydro	0
	Nuclear	0
Management procedure of residue		Landfilling
Composting process		In vessel
Gas recovery system		Not available
Energy recovery		Not available
Annul precipitation, mm		2000
Landfill lining facility		Not available
Leachate collection system		Not available

Results and discussion

Quantity of collected and transported MSW

The field survey reveals that there are 11 SHCPs having capacity of 3000 kg each and 27 large LHCPs having capacity of 5000 kg each; 12 DCRs and 17 SDSs at different locations in Khulna city. The study also finds that the total quantity of collected and transported MSW from SDS, LHCP, SHCP and DCR to FDS is 374 t d^{-1} as shown in Table 2. From FDS only 18 t d^{-1} of MSW is directly used for the composting purpose by non-government organization. Therefore, the quantity of MSW managed through landfilling in FDS is 356 t d^{-1}.

Table 2 Quantity of collected and transported MSW by KCC in Khulna city

Name of the sites	Quantity of MSW (t d^{-1})		
(Number of sites)	Dry season	Wet season	Average
Secondary disposal sites (17)	158	209.5	183.8
Large hauled container points (27)	84.3	114	99.1
Small hauled container points (11)	16.5	15.3	15.9
Distinct collection routes (12)	68.5	82	75.3
Total			374

Modelled scenarios

Table 3 represents the description of seven modelled scenarios for sustainable waste management system in Khulna city. The present practice of MSWM in Khulna is chosen as the baseline scenario in which recycling is considered as 9.1% (37.23 t d^{-1}) from the authors' another study [7], composting is considered as 4.4% (18 t d^{-1}) from field investigation and landfilling is considered as 86.5% (356 t d^{-1}) from field survey of the total managed waste (411.23 t d^{-1}). In modelled scenarios, an incineration technique in MSW management is not considered due to no facility practically in Khulna city. The baseline scenario is used as the reference against which modelled scenarios 1 to 4 are measured. The scenarios 5 to 7 represent the combination of percentage of different MSW management technique. It is to be noted that based on composition of MSW in Khulna city, the maximum percentage of compostable and recyclable MSW is considered in modelled scenario 7.

Table 3 Description of the modelled scenarios

Modelled scenarios	Composting (%)	Recycling (%)	Landfilling (%)
Baseline scenario (S-0)	4.4	9.1	86.5
Scenario 1 (S-1)	26.3	9.1	64.6
Scenario 2 (S-2)	52.6	9.1	38.3
Scenario 3 (S-3)	71.0	9.1	19.9
Scenario 4 (S-4)	4.4	13.6	82.0
Scenario 5 (S-5)	26.3	13.6	60.1
Scenario 6 (S-6)	52.6	13.6	33.8
Scenario 7 (S-7)	71.0	13.6	15.4

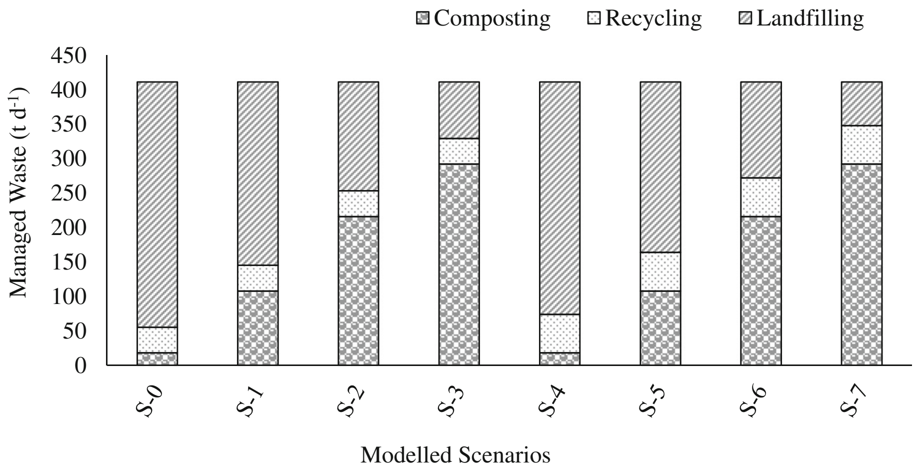

Fig. 3 Amount of managed waste at different modelled scenarios

It is estimated that the recyclable waste in the city is about 14.2%, and compostable food and vegetable waste is about 78.9% from the composition of solid waste of Khulna city [19]. In the scenario 1 (S-1), the composting is increased to six times of the baseline scenario (26.3%) because of present existing facility of composting technique by a non-government organization named Rural Unfortunates Safely Talisman Illumination Cottage which is locally called RUSTIC, recycling is considered at the same of the baseline scenario (9.1%) and landfilling is decreased to 64.6%. This scenario emphasizes composting technique of MSW in Khulna city [11]. Similiarly in the scenario 2 (S-2), the composting is increased to twelve times of baseline scenario (52.6%), the recycling is considered at the same level of the baseline scenario (9.1%) and landfilling is decreased (38.3%). The reason for the further increment of the percentage of composting of MSW is to compare the amount of emission reduction of different environmental parameters. In the scenario 3 (S-3), the composting is increased to the highest level as 71.0% (i.e., 90% of compostable food and vegetable waste) due to the available quantity of compostable MSW excluding losses in collection, transportation, and sorting from other MSW, the recycling is at the same of the baseline scenario (9.1%) and landfilling is decreased (19.9%).

In the scenario 4 (S-4), the recycling is increased to its highest level of maximum recycleable MSW as 13.6% excluding 5 to 6% material losses, composting is considered at the same level of the baseline scenario (4.4%) and landfilling is decreased (82.0%).

In case of scenario 5 (S-5), a combination is made through consideration of composting level as similiar to S-1 and recycling level as similar to S-4. In case of scenario 6 (S-6) composting level is considered as similiar to S-2 and recycling level as similar to S-4. In case scenario-7 (S-7), composting level is considered as similiar to S-3 and recycling level as similar to S-4. Figure 3 represents the amount of managed waste at different modelled scenarios.

Table 4 Emission of GHGs from modelled scenarios in net LCI

Modelled scenarios	Emission of GHGs (kg CO_2 eq d^{-1})							Emission reduction (%)
	R	C	L	TWMS	VMDC	RRM	Net LCI	
S-0	23.9	4900	769,833	774,757	−86,636	31,465	719,586	–
S-1	23.9	29,398	580,803	610,225	−86,636	31,465	555,054	22.9
S-2	23.9	58,795	353,967	412,786	−86,636	31,465	357,615	50.3
S-3	23.9	79,485	194,321	273,830	−86,636	31,465	218,659	69.6
S-4	36.1	4900	751,605	756,541	−130,642	47,447	673,346	6.4
S-5	36.1	29,398	562,575	592,009	−130,642	47,447	508,814	29.3
S-6	36.1	58,795	335,739	394,570	−130,642	47,447	311,376	56.7
S-7	36.1	79,485	176,093	255,614	−130,642	47,447	172,419	76.0

R Recycling, *C* Composting, *L* Landfill, *TWMS* Total waste management system; *VMDC* Virgin material displacement credit, *RRM* Reprocessing of recycled materials, *LCI* Life cycle inventory

Table 5 Emission of acidic gases in total waste management system

Acidic gases	Modelled scenarios							
	S-0	S-1	S-2	S-3	S-4	S-5	S-6	S-7
NOx (kg d^{-1})	43.6	42.0	40.2	38.8	43.4	41.8	39.9	38.6
SOx (kg d^{-1})	30.3	25.6	20.0	16.1	29.5	24.8	19.2	15.3
HCl (kg d^{-1})	5.9	4.4	2.7	1.5	5.7	4.3	2.5	1.3

Life cycle inventory analysis

Based on the data gathered at the inventory analysis stage, the IWM Model was run for total managed waste of 411.23 t d^{-1} in each scenario. The results of the simulation were evaluated on the environmental aspects for all the scenarios as described below. It is to be noted that in all tables, positive values indicate energy consumed or emission released and negative values indicate energy recovered or emissions reduced.

Table 4 shows the summary of GHGs emission from different modelled scenarios. The highest emission of GHGs (719.6 t CO_2 eq d^{-1}) was found in S-0 due to the highest percentage of landfilling (86.5%) and lowest percentage of recycling (9.1%) as well as composting (4.4%). On the other hand the lowest emission of GHGs (172.4 t CO_2 eq d^{-1}) was found in S-7 due to the lowest percentage of landfilling (15.4%) and highest percentage of recycling (13.6%) as well as composting (71.0%). The maximum reduction of GHGs as calculated by Eq. (1) was found in S-7 as 76% compared to baseline scenario.

Table 5 shows the acidic gases emission from different modelled scenarios in total waste management system. The emission of acid gases such as Nitrogen Oxides (NOx), Sulfur Oxides (SOx) and Hydrochloric acid (HCl) were calculated by the model. In total waste management system, the highest emission of acidic gases was found in S-0 due to the highest percentage of landfilling (86.5%) and lowest percentage of recycling (9.1%) as well as composting (4.4%). On the other hand the lowest emission of acidic gases was found in S-7 due to the lowest percentage of landfilling (15.4%) and highest percentage of recycling (13.6%) as well as composting (71.0%). In S-7, the maximum reduction of emission of NOx, SOx and HCl was found to be 12, 50 and 78% respectively compared to baseline scenario.

Table 6 Emission of smog precursors in total waste management system

Smog precursors	Modelled scenarios							
	S-0	S-1	S-2	S-3	S-4	S-5	S-6	S-7
NOx (kg d^{-1})	43.6	42.0	40.2	38.8	43.4	41.8	40.0	38.6
PM (kg d^{-1})	109.8	101.0	90.5	83.2	105.8	97.0	86.5	79.1
VOCs (kg d^{-1})	218.7	171.1	113.9	73.7	213.9	166.2	109.0	68.8

NOx Nitrogen oxide, *PM* Particulate matter, *VOCs* Volatile organic compounds

Table 7 Emission of heavy metal and organics to air in total waste management system

Modelled scenarios	Emission of heavy metal and organics to air (mg d^{-1})			
	Lead	Mercury	Cadmium	Dioxins (TEQ)
S-0	1858	17	675	0.031
S-1	1476	15	523	0.024
S-2	1018	12	340	0.015
S-3	695	9	211	0.008
S-4	1802	17	658	0.030
S-5	1420	14	506	0.023
S-6	961	11	323	0.014
S-7	639	9	194	0.008

TEQ Toxic equivalency

Table 6 shows the emission of smog precursors such as NOx, particulate matter (PM), volatile organic compounds (VOCs). In total waste management system, the highest emission of smog precursors was found in S-0. On the other hand the lowest emission of smog precursors was found in S-7 due to the lowest percentage of landfilling and highest percentage of recycling as well as composting. Also the maximum reduction of emission of NOx, PM, VOCs was found in S-7 as 12, 28 and 69%, respectively compared to baseline scenario.

Table 7 represents the emission of heavy metal and organics to air in total waste management system. In case of lead emission, the highest emission was found in S-0 as 1858 mg d^{-1} due to the highest percentage of landfilling. Conversely the lowest emission was found in S-7 as 639 mg d^{-1} which is 65.6% lower compared to baseline scenario. In the same way the maximum emission reductions of mercury, cadmium and dioxins were found in S-7 as 47, 71 and 76% respectively compared to baseline scenario.

In case of emission of heavy metal and organics to water in total waste management system, the lowest emission to water was found in S-7 as shown in Table 8.

Table 8 Emission of heavy metal and organics to water in total waste management system

Modelled scenarios	Emission of heavy metal and organics to water				
	Lead (mg d^{-1})	Mercury (mg d^{-1})	Cadmium (mg d^{-1})	BOD (kg d^{-1})	Dioxins (TEQ) (mg d^{-1})
S-0	123,671	1739	176,764	2349	0.024
S-1	94,852	1332	135,356	1799	0.018
S-2	60,269	843	85,668	1138	0.011
S-3	35,929	499	50,697	673	0.007
S-4	118,727	1670	169,659	2255	0.023
S-5	89,908	1262	128,251	1704	0.017
S-6	55,325	773	78,563	1043	0.010
S-7	30,985	429	43,592	579	0.006

BOD Biochemical oxygen demand, *TEQ* Toxic equivalency

Table 9 Quantity and the reduction of residual waste

Modelled scenarios	Residual waste (t d^{-1})	Reduction of residual waste (%)
S-0	358.8	–
S-1	273.3	24
S-2	170.7	54
S-3	98.5	73
S-4	341.1	5
S-5	255.6	29
S-6	153.0	57
S-7	80.8	78

In S-7, the maximum emission reductions of lead, mercury, cadmium, biochemical oxygen demand and dioxins were found to be approximately 75% as compared to baseline scenario.

Table 9 shows quantity of residual waste in total waste management system. In case of S-0, the maximun residual waste was found as 358.8 t d^{-1} due to larger quantity of landfilling. On the other hand, the minimum residual was found in S-7 as 80.8 t d^{-1}. In addition the maximum reduction of residual waste was found in S-7 as 78%.

Table 10 repersents amount of energy consumption or recovery of modelled scenarios in various waste management techniques. The maximum net energy recovering were found in S-4 (−1491 GJ d^{-1}), S-5 (−1494 GJ d^{-1}), S-6 (−1499 GJ d^{-1}) and S-7 (−1502 GJ d^{-1}) considering the large contribution of virgin material displacement credit (−2276 GJ d^{-1}). The variation of net energy recovery among these scenarios was insignificant, or the minimum net energy recovering were found in S-0 (−962 GJ d^{-1}), S-1 (−966 GJ d^{-1}), S-2 (−971 GJ d^{-1}) and S-3 (−974 GJ d^{-1}). In case of all the scenarios, net energy recovery increases with the increase in the percentage of recycling, although amount of energy is insignificant compared to other waste management technique.

Table 10 Energy consumption in different modelled scenarios

Modelled scenarios	Energy consumed or recovered (GJ d^{-1})						
	R	C	L	TWMS	VMDC	RRM	Net LCI
S-0	0.03	0.26	76.4	76.7	−1509	470	−962
S-1	0.03	0.26	76.4	76.7	−1509	470	−966
S-2	0.37	0.26	67.7	68.3	−1509	470	−971
S-3	0.50	0.26	64.3	65.1	−1509	470	−974
S-4	0.03	0.40	75.8	76.2	−2276	709	−1491
S-5	0.19	0.40	71.8	72.4	−2276	709	−1494
S-6	0.37	0.40	67.0	67.8	−2276	709	−1499
S-7	0.50	0.40	63.7	64.6	−2276	709	−1502

R Recycling, *C* Composting, *L* Landfilling, *TWMS* Total waste management system; *VMDC* Virgin material displacement credit, *RRM* Reprocessing of recycled materials, *LCI* Life cycle inventory

Conclusions

The main conclusions drawn from the present study are as follows:

(i) Scenario 7 has the least emission of greenhouse gases, acidic gases, smog precursors, heavy metal and organics to air as well as to water than that of all other scenarios.
(ii) Scenarios 4 to 7 consume less energy compared to other scenarios.
(iii) Scenario 7 has the minimum residual waste than that of all other scenarios.

Therefore, it can be concluded that scenario 7 is the best waste management system for Khulna city of Bangladesh.

Acknowledgements
The authors wish to express thanks to Khulna University of Engineering & Technology for the financial support to complete this research. The authors of this article also wish to express thanks to all officers and staff of conservancy the department of Khulna City Corporation for providing relevant data and assistance in this study.

Authors' contributions
Both authors read and approved the final manuscript.

Competing interests
The authors declare that they have no competing interests.

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Received: 14 June 2018 Accepted: 12 March 2019
Published online: 30 April 2019

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