Environmental comparative assessment of different waste strategies in developing regions

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Abstract

Waste management in the Republic of Kazakhstan is still in its infancy: the major fraction of the municipal solid waste (MSW) is disposed of in open dumps and landfills, while only some pilot plants equipped with mechanical separation systems are available to date. This situation is responsible for potential environmental impacts as well as damages to public health. Accordingly, alternative waste management systems must be developed to move towards a more sustainable framework. In this context, the primary goal of this study was to evaluate the potential environmental benefits of implementing alternative waste management schemes based on both low-waste generation and renewable energy production. The current situation regarding the capital of the country (Astana) was considered as basis for calculations. The Life Cycle Assessment (LCA) methodology – recognised as one of the most relevant environmental assessment tools regarding MSW management – was followed to assess the environmental performance of various technologies. According to the results, the proposed waste management scenarios were demonstrated to have a more environmental-friendly performance compared to current practices, mainly due to the environmental credits associated with the generation of renewable energy. Moreover, the reuse of recycled materials (primarily paper and cardboard) should also have a favourable influence to offset land use related problems. The major findings of the present study are expected to help to promote the development of more sustainable waste management technologies that comply with future environmental regulations in Kazakhstan and other developing countries in an analogous context.

Keywords: Municipal Solid Waste (MSW); waste management; environmental profile; developing countries; Kazakhstan.

1. Introduction

In the last decades, policies regarding municipal solid waste (MSW) management have changed in response to societal and environmental concerns [1-3]. However, in developing countries, the trend of continuous growth in waste generation has not been followed by the development of modern waste management practices [3-7]. Indeed, both insufficient collection systems and inadequate disposal facilities have led to potential risks on public health and environmental pollution [6, 8-9]. This highlights the importance of promoting a more comprehensive analysis in this field with the aim of providing a waste management plan that meets their needs and addresses their major environmental problems [4, 10].

Accordingly, landfilling is still the most widespread alternative for MSW management in the Republic of Kazakhstan. Thus, although several mechanical separation treatment plants have been developed to date – mainly based on the recovery of some materials – the valorisation of the organic waste fraction through renewable energy generation has not yet been established in the country [4]. However, increasing environmental concerns and public pressures have forced to make progress towards more environmental-friendly strategies for MSW treatment [4]. The Life Cycle Assessment (LCA) has been recognised as one of the most relevant environmental assessment tools regarding MSW management [11-12]. Indeed, according to literature, this methodology has been widely used to evaluate the potential environmental damages from different waste treatment configurations [11-16]. On the basis of the LCA guidelines [17], this study aimed to estimate the environmental performance of different alternative schemes for MSW management in Kazakhstan and evaluate their potential environmental benefits in comparison with current practices in the country.

2. Materials and methods

2.1. Goal and scope

The research area considered in this study is located in Astana, the current capital city of Kazakhstan, with an average population of 872,619 inhabitants and an MSW generation rate of around 1118 t/day in 2016, equivalent to 1.3 t/(inh·day) [4]. The average composition of municipal waste in Astana is displayed in **Table 1**. However, it should be noted that, due to the absence of a properly waste collection system, only around 800 t/day (72% of the total MSW generated) is subjected to further processing [4]. At present, waste management systems mainly based on the mechanical separation of a small fraction of recyclable materials are being prioritised instead of landfilling practices still available in other regions of the country. However, the implementation of alternative treatment schemes is also analysed to move towards a more sustainable waste management strategy in the city [4].

In this context, the present study has focused its attention on two main objectives: (i) the assessment of the environmental impacts of the current waste management practice in Astana and (ii) the comparison with the environmental performance of alternative management schemes proposed as potential improvement configurations. A cradle-to-gate approach was considered, encompassing all stages from waste collection and transportation up to the final management and/or disposal of the different MSW fractions. Since both recycled materials and renewable energy can be obtained as main outputs of the system, the environmental benefits from their further use as substitutes for non-recycled materials and fossil energy, respectively, were also considered to address the allocation requirements (system expansion approach).

2.2. Functional unit

The aim of the functional unit (FU) is to provide the necessary reference to ensure comparability of LCA results from different sources [17]. Waste mass-based FUs are commonly used in LCA studies involving waste management systems [12-13, 15, 18]. A functional unit of 1 ton of MSW was considered in this study as a common basis for comparison in agreement with literature.

2.3. Description of alternative management scenarios

A total of four alternative scenarios were considered for MSW management: mechanical treatment without biogas valorisation (current scenario – S0), landfilling (S1), mechanical treatment with partial (50%) biogas valorisation (S2) and mechanical treatment with total (100%) biogas valorisation (S3). A CHP unit was assumed to be used for energy generation from biogas combustion. The main stages of each management scheme are shown in **Fig. 1 – 4**.

The same input flow and MSW composition (**Table 1**) was considered for all the scenarios; similarly, a minor fraction (6%) of potentially recovered material is recycled in all scenarios (except landfilling) for their further use, to avoid the production of their analogous in the market. The following recovered materials were included: paper/cardboard (3.1%), plastics (2.0%), glass (0.6%) and metals (0.3%).

2.4. Life Cycle Inventory (LCI) analysis

Main input and output flows for the different scenarios are displayed in **Table 2**. A common approach for data collection was followed to ensure the reliability of the comparative results. Thus, the following inventory information was included: MSW input flow, transportation activities, electricity requirements and energy generation (only in case of biogas valorisation), land use and diffuse emissions (in terms of CH_4 and CO; biogenic CO_2 was assumed to be delivered to the atmosphere without related environmental impacts).

Primary inventory data (from personal communications) was used regarding MSW flow and composition, transport distances and collection system (transport fleet, collection frequency) as well as recovered rates for recyclable materials (**Table 2**).

However, secondary data was also compiled from literature to complete the inventory of the different systems in the absence of primary information. Greenhouse gas (GHG) emissions from landfilling were estimated according to Abeliotis et al. [13] and Bernstad and la Cour Jansen [14]. Similarly, electricity consumption rate (≈43 kWh/t MSW) from MBT facilities was also estimated in agreement with related studies in the literature [13-14]. The energy potential of biogas (only in case of biogas combustion) was assumed to be 5.67 kWh/m^3 biogas, taking into account a calorific value of 9.45 kWh/m^3 CH_4 and a composition of 60% CH_4 (40% CO_2) [19]; average rates of 40% and 48% was considered for electric and thermal efficiency, respectively [20].

Finally, ecoinvent® database [21-24] was used for background inventory regarding energy (electricity and heat) generation, diesel consumption (from transportation) and the production of recycled materials (avoided processes).

2.5. Life Cycle Impact Assessment (LCIA)

The following impact categories were selected to evaluate the environmental profile of the different scenarios on the basis of the characterisation factors provided by the ReCiPe Midpoint (H) method [25]: climate change (CC), terrestrial acidification (TA), freshwater eutrophication (FE), marine eutrophication (ME) and fossil depletion (FD). Land use (LU) was also considered taking into account the land occupied by waste management facilities (mainly due to landfill surface).

3. Results and discussion

3.1. Environmental results of current scenario (S0)

The environmental impacts associated with the current MSW management strategy in Astana (S0) are shown in **Fig. 5**. According to the results, the energy requirements for the operation of the mechanical treatment plant was the main contributor to the environmental burdens in all the impact categories (up to 38%), except for CC, where the emission of GHGs (CH_4 and CO) derived from the degradation of organic waste in the landfill is responsible for the greatest impacts (around 95%). Transport activities from waste collection to mechanical treatment plant location have a minor relevance in the overall results.

Conversely, the recovery and subsequent reuse of a fraction of the recyclable materials have a beneficial effect on most impact categories (except for CC), especially due to recovered paper and cardboard (from 17% to 97%) as well as recovered plastics (from 2% to 54%). Special attention should be paid to the environmental-friendly contribution to LU from paper/cardboard recycling; it is directly linked to the arable land required for the cultivation of raw materials for the industrial production of both paper and cardboard. Finally, no environmental credits are registered from power generation since no biogas valorisation from landfilling waste is available today in the mechanical treatment plant.

3.2. Comparative environmental results (S0 – S3)

Characterisation results for the different scenarios and impact categories are reported and compared to the current situation (S0) in **Table 3**. In view of the results, those scenarios where biogas valorisation is taken into consideration – S2 and S3 – show the best environmental performances. The production of renewable energy from the use of the CH_4 (biogas) generation in the landfill is the main responsible for such favourable results from an environmental perspective. Consequently, CH_4 is not released into the atmosphere, so that GHG emissions are deducted at source. This is the rationale behind the net negative balance of S3 in CC. Moreover, when land use (LU) is evaluated individually, similar results can be found for all scenarios (except for S1). This highlights that the generation of renewable energy has not a relevant contribution in this category, while recovered materials exert the greatest influence, in agreement with previous results (S0 – **Fig. 5**).

4. Conclusions

The principles of the LCA methodology has been followed in this study to analyse the potential environmental credits resulting from the implementation of alternative MSW management strategies in Kazakhstan, mainly based on biogas valorisation. Primary data regarding actual MSW management in Astana (capital of the country) was assumed as base scenario; the worst-case scenario (landfilling) was also considered for comparison. According to the results, those scenarios where the generation of renewable energy from biogas combustion is prioritised (in detriment of GHGs released into the atmosphere) show the best environmental performance in most impact categories; indeed, the higher the biogas valorisation, the most-environmental friendly results. The only exception is when land use is evaluated, which is strongly dependent on the environmental credits derived from the recovery of paper and cardboard, as an alternative of massive cultivation practices associated with its large-scale industrial production.

Table 1. Average MSW composition in Astana [4].

Waste fraction	Percentage (%)	Mass flow (t/day)
Organics (food waste)	27.6	308
Plastics	15.5	173
Glass	14.9	167
Paper/Cardboard	11.2	125
Garden	2.80	31.3
Metals	0.95	10.6
Wood	0.60	6.71
Others	26.5	296
TOTAL	100	1118

Table 2. Average annual inventory data (primary and secondary sources) for the different scenarios: S0 – mechanical treatment plant; S1 – landfilling; S2 – mechanical treatment + 50% biogas valorisation; S3 – mechanical treatment + 100% biogas valorisation.

Inputs/Outputs	S0	S1	S2	S3	Data sources
Inputs					
MSW flow (t)	292000	292000	292000	292000	Primary data
Electricity (kwh)	12556000	0.00	12556000	12556000	Literature [13, 14]
Transportation (t·km)	5.50	5.50	5.50	5.50	Primary data
Land use (ha)	1.22	1.25	1.22	1.22	Primary data
Outputs - emissions					
CH_4 (t) (air)	13932	14296	6966	0.00	Literature [13, 14]
CO (kg) (air)	444	456	444	444	Literature [13, 14]
Outputs - energy					
Electricity (avoided)	-	-	38722109	77444217	Literature [20]
Heat (avoided)	-	-	46466530	92933060	Literature [20]
Outputs – materials					
Paper/cardboard (recycled)	3847100	-	3847100	3847100	Primary data
Plastics (recycled)	2482000	-	2482000	2482000	Primary data
Glass (recycled)	744600	-	744600	744600	Primary data
Metals (recycled)	372300	-	372300	372300	Primary data

Table 3. Comparative environmental results for the different scenarios per ton of MSW treated (FU): S0 – mechanical treatment plant; S1 – landfilling; S2 – mechanical treatment + 50% biogas valorisation; S3 – mechanical treatment + 100% biogas valorisation.

Impact category	Units	S0	S1	S2	S3
Climate Change (CC)	kg CO_2 eq	1174	1125	478	-219
Terrestrial Acidification (TA)	kg SO_2 eq	$-6.61 \cdot 10^{-2}$	$3.24 \cdot 10^{-3}$	-0.53	-1.00
Freshwater Eutrophication (FE)	g P eq	-6.77	$6.10 \cdot 10^{-2}$	-25.5	-44.1
Marine Eutrophication (ME)	g N eq	-6.84	0.17	-20.4^{2}	-33.9
Land use (LU)	m^2	-90.9	$4.29 \cdot 10^{-2}$	-96.1	-101
Fossil depletion (FD)	kg oil eq	-13.5	0.27	-44.1	-74.7

Figure captions

Fig. 1 Main stages of mechanical treatment plant scenario (S0)

Fig. 2 Main stages of landfilling scenario (S1)

Fig. 3 Main stages of mechanical treatment plant + 50% biogas valorisation scenario (S2)

Fig. 4 Main stages of mechanical treatment plant + 100% biogas valorisation scenario (S3)

Fig. 5 Environmental results associated with the current MSW management scenario (S0) in Astana. Note: positive values (above x-axis) represent environmental impacts while negative results (below x-axis) make reference to environmental credits. Acronyms: CC = climate change; TA = terrestrial acidification; FE = freshwater eutrophication; ME = marine eutrophication; LU = land use; FD = fossil depletion.

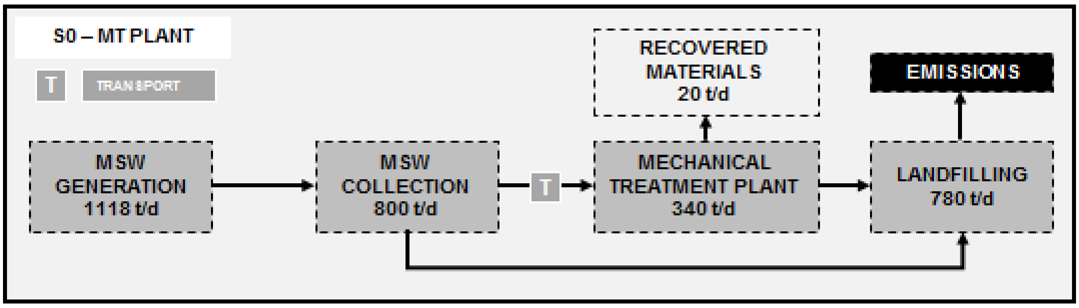

Fig. 1

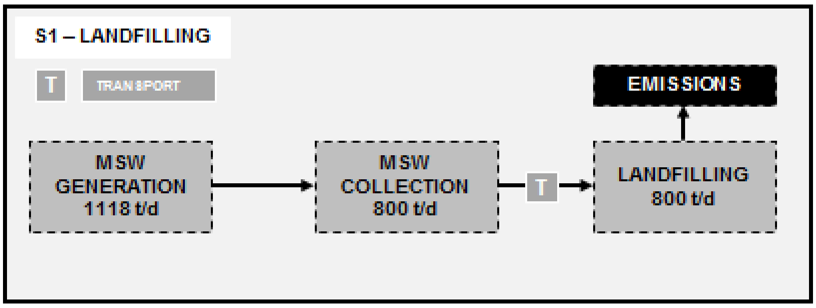

Fig. 2

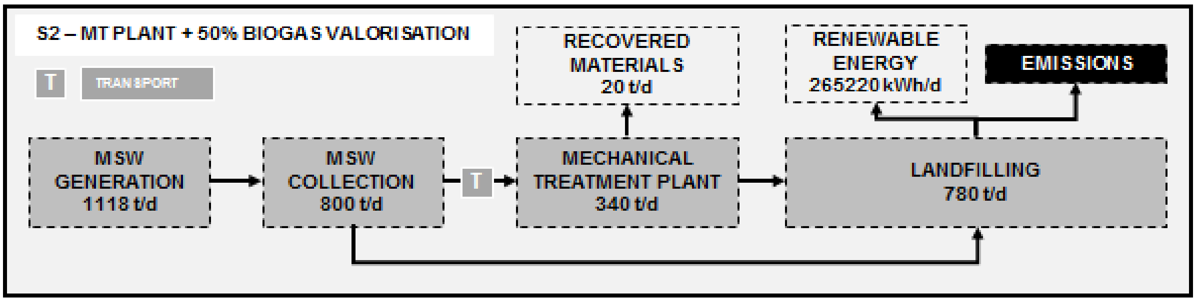

Fig. 3

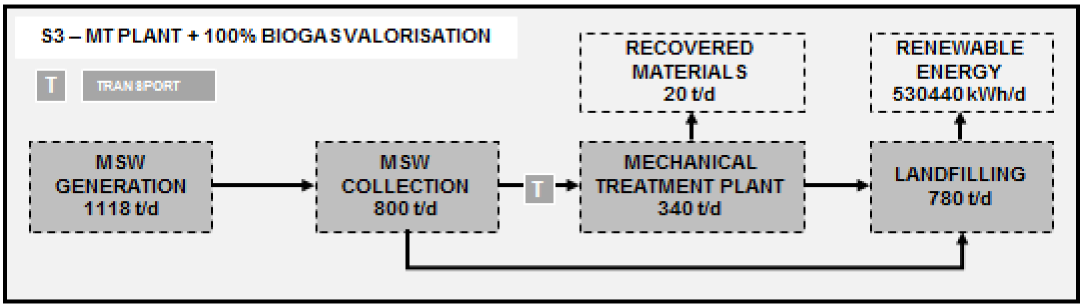
S3 – MT PLANT + 100% BIOGAS VALORISATION
T
TRANSPORT
RECOVERED MATERIALS 20 t/d
RENEWABLE ENERGY 530440 kWh/d
MSW GENERATION 1118 t/d
MSW COLLECTION 800 t/d
T
MECHANICAL TREATMENT PLANT 340 t/d
LANDFILLING 780 t/d

Fig. 4

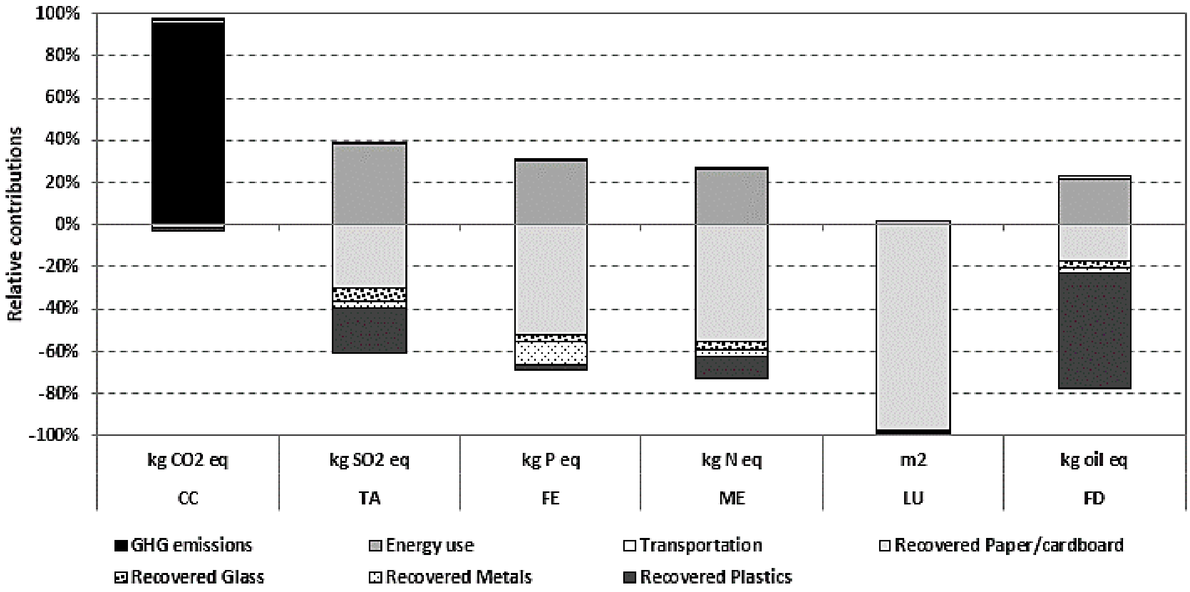
100%
80%
60%
40%
20%
0%
-20%
-40%
-60%
-80%
-100%
Relative contributions
kg CO2 eq
CC
kg SO2 eq
TA
kg P eq
FE
kg N eq
ME
m2
LU
kg oil eq
FD
GHG emissions
Energy use
Transportation
Recovered Paper/cardboard
Recovered Glass
Recovered Metals
Recovered Plastics

Fig. 5

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