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Multi-criteria analysis of municipal solid waste treatment technologies to support decision-making in Kisumu, Kenya

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ABSTRACT

The directive to close the dumpsite in Kisumu, Kenya has made the search for alternative solid waste treatment and disposal technologies urgent. The aim of this research is to support the decision-making process by analyzing multiple socioeconomic and environmental parameters of salient solid waste treatment options. We used multi-criteria analysis to assess and compare anaerobic digestion, sanitary landfill, bioreactor landfill, and incineration. Informed by field observations and interviews, the chosen assessment criteria were economic costs, electricity generation, GHG emissions, land footprint, air pollution, soil and water contamination, and compatibility with recycling efforts. A literature review yielded quantitative and qualitative data that supported the analysis and the ranking of solutions according to performance in each criterion. Our analysis shows that anaerobic digestion is a suitable solution for Kisumu, due to its reduced environmental impacts, production of electricity and fertilizer, suitability to treat the large organic waste stream generated in the city, and compatibility with independent recycling activities. Landfilling represents a cheap solution; however, previous failed initiatives indicate that finding available land close to main waste generators is a challenge. Incineration is costly and requires advanced air quality control equipment and high combustibility of incoming waste, which is not the case for Kisumu, where over 60% of waste stream is organic/wet. Our results and recommendations are targeted for the Kisumu case, but they can be relevant for researchers and policymakers elsewhere, especially in low- and middle-income cities facing similar challenges.

1. Introduction

Solid waste is an important sustainability issue since it can harm public health and the biosphere at multiple levels, if not handled properly (UNEP and ISWA 2015). In most cities of low- and middle-income countries, the responsibility and costs for waste management tends to fall on local governments with limited capacities to address the issue (Kaza et al., 2018). The situation is even more challenging in Africa, where the generation of waste is expected to grow significantly more than in any other region of the world in the next decades, while waste collection and disposal services are already inadequate (UNEP and ISWA 2018). More than 90% of the waste generated on the continent goes to uncontrolled dumpsites and landfills (UNEP and ISWA 2018). Simultaneously, waste represents lost economic opportunities, where it is estimated that 70% of the African waste is recyclable, but only 4% is recycled, mostly by informal waste pickers (UNEP and ISWA 2018).

The same challenge prevails in Kisumu, Kenya, a city located in the shores of Lake Victoria and capital of Kisumu County. The city generates 338 tonnes/day of municipal solid waste, from which over 63% is organic (Ngusale et al., 2017). The only disposal site in the County, Kachok dumpsite, is located approximately 1.5 kms from Kisumu's city center (Awuor et al., 2019). Data on the city's population and waste generation are presented in Table 1.

The local waste crisis, attempts to relocate the dumpsite and improve on-site management date back to 2000 and were documented by Awuor et al., 2019. Only 20–35% of the waste is collected (Sibanda et al., 2017) by municipal collection services and by private micro-entrepreneurs, who receive a small collection fee from households

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Table 1
Population and waste characterization data for Kisumu.

Parameter	Value	Unit	Source
Total population in Kisumu County	1 155 574	inhabitants	Kenya National Bureau of Statistics 2019
Population in Kisumu City	397 957	inhabitants	Kenya National Bureau of Statistics 2019
Projected population growth	2.8	%/year	Munala and Moirongo, 2011
Kachok dumpsite size	2.73	ha	Ngusale et al., 2017
Total waste generated in Kisumu City	338	tonne/day	Ngusale et al., 2017
Total waste generated in Kisumu City	123 425	tonne/year	Ngusale et al., 2017
Organic waste generated in Kisumu City	77 881	tonne/year	Ngusale et al., 2017
Paper waste generated in Kisumu City	15 182	tonne/year	Ngusale et al., 2017
Plastic waste generated in Kisumu City	12 589	tonne/year	Ngusale et al., 2017
Glass waste generated in Kisumu City	3 950	tonne/year	Ngusale et al., 2017
Scrap metals generated in Kisumu City	1 605	tonne/year	Ngusale et al., 2017
Other waste generated in Kisumu City	12 219	tonne/year	Ngusale et al., 2017
Proportion of waste collected in Kisumu City	20–35	%	Sibanda et al., 2017

and businesses and receive additional earnings from recycling materials, especially plastic and paper (Gutberlet et al., 2016). Most households, however, still handle their own waste by dumping in public spaces, open burning or composting (County Government of Kisumu 2017).

The directive to close Kachok dumpsite has prompted discussions as to which technology to employ as an alternative disposal solution for the city of Kisumu. The aim of this research is to support the decision-making process with more precise, technical information regarding solid waste treatment options that are currently being discussed locally. Therefore, our research question is: *What are the advantages and disadvantages of different solid waste treatment options, and which one would be more suitable for Kisumu?*

2. Methodology

Our research consisted of a desk-study preceded and informed by a fieldwork phase. We used multi-criteria analysis (MCA) to compare different waste treatment technologies, using both qualitative and quantitative data retrieved from the literature. Key informant interviews and observations during the fieldwork in Kisumu were used to understand the local context and choose the relevant comparison criteria.

The fieldwork was undertaken between the 5th and 16th of August 2019, to collect background information and design the methodology together with a local research team in Kisumu. We conducted 4 semi-structured interviews with county and city government officials and one focus group discussion with the Kisumu Waste Actors Network (KIWAN), an association whose members are directly involved in waste collection, transportation and recycling. Table 2 presents information on the interviews, and the interview guide is presented in the Appendix.

We also carried out field visits to understand, e.g., dumpsite operations, existing resource recovery activities, such as pilot initiatives of anaerobic digestion in Kibuye Market and in the city's wastewater treatment plant. Interviews and site visits were scheduled by the local research team, who had already established relationships with city and county government officials, and who supported the creation of KIWAN. The interviews allowed us to understand the challenges concerning solid waste management system in Kisumu, the priorities for selecting a treatment option, as well as current plans by the government and possibilities for moving ahead after Kachok's closure. The field phase was crucial in defining, together with relevant decision makers and private entrepreneurs, the criteria we used to compare the four treatment technologies.

Answers were typed in the form of interview notes on MS Word as they were collected. Interview notes from each informant were combined together and divided into different topics, so results would be analyzed as a whole, and responses would be anonymized. Interview results are presented in a way that it is not possible to attribute responses to informants, except for KIWAN, as their challenges and priorities are not necessarily the same as those of government officials. Since we attributed KIWAN's responses to the group, we chose not to identify the focus group participants by name, in order to protect their individual identity.

A review of the literature was conducted in Scopus to locate data on the performance of the four waste disposal technologies for each of the selected criteria. The criteria and technologies were combined as keywords in the search as follows: technology name (*biodigest**, *"sanitary landfill", "bioreactor landfill", "incineration"*) + name of the criterion (*"cost", "investment", "electricity generation", "kWh", "GHG emissions", "CO_2", "water contamination", "size", etc*). Additional keywords were then added if searches were too broad (e.g., *"municipal solid waste", "full-scale plant"*).

A total of 803 results were found from 68 searches that were performed. For each search, a screening of articles' titles was done and, those that seemed relevant to the study, went through abstract screening. Only 108 articles were deemed relevant from the abstract screening and made into the final selection of consulted literature. The articles comprised research conducted in different continents, including life cycle assessments, cost-benefit analyses, modeling of different scenarios, among others. Some articles presented values from existing plants, while others presented more theoretical calculations, for no specific location.

The selected literature was browsed for each criterion, and a database was built for each treatment technology: 212 data entries were compiled for AD, 388 for SL, 145 for BL and 301 for IN. Bioreactor landfills had fewer studies from existing plants, most of them located in USA, and some were operated as small-scale cells inside sanitary landfill areas. Therefore, data concerning BL for some criteria was more limited than for the others, as it is not a as widely implemented technology.

Table 2
Interviews conducted with relevant public and private stakeholders.

Type	Date	Position and organization	Name of interviewee
Semi-structured interview	06/08/2019	Department of Environment, Kisumu City	Benard Ojwang'
Semi-structured interview	06/08/2019	Environment Chief Officer, Kisumu County	Dan Ong'or
Semi-structured interview	08/08/2019	City planner, Kisumu City	Steven Sule
Semi-structured interview	09/08/2019	Energy and Industrialization Chief Officer, Kisumu County	Daniel Okia
Focus group discussion	07/08/2019	Kisumu Waste Actors Network (KIWAN)	Several micro-entrepreneurs working with waste collection

To reduce bias, the analysis was meant to be as quantitative as possible, but qualitative data was used to fill in the gaps when quantitative data was not available. Data entries were filtered for each criterion and quantitative data was treated to standardize measurement units and allow comparison across studies. Where necessary, all economic calculations were converted to U.S. dollars (USD) based on conversion rates from late-January 2020. Data on the waste processing capacity of treatment plants that was presented in tonne/day were multiplied by 300 days to obtain annual values, when the number of operating days was not provided. One or more tables were produced for each criterion and technology, and unitary values were calculated "per tonne of MSW treated," to allow comparison between the technologies. For some criteria, it was important to segregate sanitary landfill into three sub-technologies based on landfill gas (LFG) control: without LFG control; with flaring of LFG; or with electricity generation from LFG (energy recovery). Studies that presented unitary values, but did not bring the overall waste processing capacity of the plant (neither per day or year) were avoided for those criteria where the capacity significantly affects the unitary value (such as cost).

Once all the units had been converted and unitary values had been calculated, the analysis began. In order to produce the results tables, only the values that best translated Kisumu's characteristics were included, namely, the quantity of waste treated and the level of income of the country where the treatment plant was based. This was done by considering at least 2 values from smaller plants (processing fewer than 123 000 tonnes of MSW/year, which is approximately the amount generated by Kisumu city), and at least 2 values from larger plants (more than 123 000 tonne/year). For anaerobic digestion the values considered were only for organic waste, therefore the threshold was about 77 000 tonne/year). The level of income used was based on that of the World Bank, which defines Kenya as a lower middle-income country ($1 026–$4 035 per capita), along with countries like Nigeria, Morocco, India, Vietnam, Indonesia, Honduras and Ukraine (Kaza et al., 2018). Studies from Sub-Saharan Africa were prioritized regardless of their income level (as none of them belongs to the high-income group), since cultural and climatic similarities are also relevant factors in waste generation and solutions, studies from e.g., Tanzania (low-income) and South Africa (upper middle-income) were actively included. Values which were too discrepant from the other values were actively excluded instead.

Once tables presenting the most relevant data from the literature for Kisumu's case were prepared, comparison tables of the four technologies for each criterion were created. The comparison tables bring the average and range of values from the results tables presented earlier, and gives a rank of 1, 2, 3 and 4 (i.e., 1 being the best performance and 4 the worst performance). For most criteria, the best performance is associated with lower values (e.g., lower cost, lower greenhouse gas emissions), but for electricity generation, the best performance is associated with higher values. Then, a final MCA table is presented with the ranking of all four technologies in each criterion, in an attempt to showcase the overall performance of the assessed treatment options. Each criterion is discussed individually as results tables are presented, and a final discussion with recommendations for Kisumu is done towards the end.

A limitation to this approach was the availability of data. When data was not available for lower-middle income or Sub-Saharan African countries, data from upper-middle income countries was then considered, such as from China, Brazil and Malaysia. There was no need to consider low-income countries, since most of them are located in Sub-Saharan Africa and our database did not have any studies from low-income countries located elsewhere (i.e. Haiti, Nepal, Afghanistan and North Korea) (Kaza et al., 2018). Unfortunately, that was not always enough to gather significant data and, in exceptional circumstances, studies from high-income countries such as USA and Saudi Arabia were included. Data was also not always available for at least 2 smaller and 2 larger plants, and that is reflected in some tables having less than 4 data entries for each technology. Another limitation was that values from the literature are only an indication of performance of each technology, for comparison purposes, as so many variables would influence an actual plant's performance. Still, we think our approach allows us to discuss advantages and disadvantages of each technology and provide a better technical basis for decision-making in Kisumu.

Our results section is structured as follows: first, the results from the field are presented in Section 3.1, and these primary results fed our choice of technologies and criteria for the analysis, which are described in Section 3.2. Section 3.3 brings the multi-criteria analysis, where each criterion was explored and discussed. Finally, based on the MCA, field observations and interviews, we give recommendations for Kisumu in Section 3.4.

3. Results and analysis

3.1. Fieldwork results: understanding the challenges and possible solutions

One of the starting points of our research, the consultation with key informants was useful for us to understand the peculiarities of Kisumu's waste management system, existing solutions and future plans to address the solid waste issue, as well as the priorities for decision-making on a new technology system. Through the conversations we had, it became clear that the waste issue in Kisumu is largely influenced and shaped by political will and public opinion, and our technical contribution was largely welcomed by consulted stakeholders.

We were informed by the local research team that the directive to relocate Kachok dumpsite was an election campaign promise made by elected Kisumu County governor Anyang' Nyong'o (The Sunday Standard 2017), as the precarious sanitary conditions of the site and its proximity with residential and commercial areas was a growing reason for public discontent. Government officials seemed to be confident about the closure of Kachok, which was already having its stabilized waste relocated to an empty quarry outside of the city (whose precise location was not shared by any of our informants), and trees were being planted as rehabilitation efforts to turn the dumpsite into a park. These efforts were confirmed during our site visit of the dumpsite, which had also been fenced, preventing people from outside to see inside, as shown in Fig. 1. However, we observed that the back portion of the site, furthest from the street, still has lots of fresh waste (Fig. 2), and we witnessed one waste collection vehicle disposing more waste (Fig. 3).

KIWAN informants expressed concerns about the closure and the destination of new waste, as some of them were private collectors of household waste who took their collected waste to the dumpsite. Since waste collection by the municipality is insufficiently done by only one truck, some private entrepreneurs have set up their own businesses in providing private collection services to households and commercial establishments. Most of the recycling happening in Kisumu is done by these micro-enterprises, but their collection services also include non-recyclable waste (Gutberlet et al., 2016). What to do with the fresh waste generated by the city continued to be the most pressing challenge, as no sustainable, long-term final disposal solution had been implemented. It became clear that the government was concentrating its efforts in reducing Kachok's nuisance to neighboring communities, but this was, to us, only a partial solution. Among other challenges mentioned by public authorities were:

- Finding available land at a reasonable distance from the city center for treatment or final disposal facilities;
- Strong public opposition to implementing a new landfill (also known as NIMBY – "not in my backyard" syndrome), requiring strong public engagement for future proposed solutions;
- Increasing waste generation due to change in consumption patterns and population growth;
- Influence of politicians who have limited understanding of technical projects over discussions on the issue and, ultimately, decisions;
- Limited financial resources to implement infrastructure projects;

Fig. 1. Kachok dumpsite under rehabilitation: fence to the right, waste removal and soil movement activities, and planting of trees in the distance.

Fig. 2. Back portion of Kachok still housing fresh waste, and a compactor machine.

- Inadequate destination of hazardous waste, such as medical and electronic waste, and
- Low access to electricity at the County level.

The challenges for KIWAN informants were more on waste collection and household segregation as opposed to the search for a final waste disposal technology. The greatest concern was related to how to enforce payment for waste collection as, reportedly, many households refuse to pay for collection services. Certain households instead dispose waste inappropriately, by burning or dumping by roadsides, raising public health concerns for the whole society. Other challenges for their business were segregation at source by households, informality (prices were negotiated individually with each household), and economic sustainability (significant level of late or no payments). They claimed that conditions to operate their services were poor, for instance, their improvised collection vehicles required lots of maintenance and keeping them clean was almost impossible, while some have claimed to have gotten injured when performing their duties. Informants also claimed lack of clear communication channels between them and the authorities, the lack of law enforcement against littering and waste dumping, and the lack of a formal licensing/authorization process to legitimize and compensate the collection and proper disposal by micro-entrepreneurs, as there were reportedly illegitimate waste collectors who charged for collection services but would illegally dump the waste.

During our visit to Kachok, we were welcomed by the dumpsite manager, an employee who was hired in the city's efforts of improving the environmental and sanitary conditions of the site, as described by Awuor et al., 2019. Large birds such as pelicans were looking for food in the dumpsite, and waste burning was probably practiced by waste pickers to help sort out the waste. There were about 50 waste pickers *living* in the dumpsite by the time of our visit. Interestingly, none of our key informants had mentioned the existence of waste pickers at the dumpsite. Those are believed to be very poor people with extreme levels of vulnerability, who would scavenge the newly arrived waste for food or recyclables that could be sold for money. Fig. 4 shows the shelter conditions under which these people were living at the dumpsite. It is our conscious choice to not disclose any pictures of the people living in the dumpsite, to avoid them suffering from retaliation by local authorities.

Fig. 3. Waste being disposed in Kachok by a collection vehicle, and waste pickers awaiting to sort out recyclables and other valuable materials.

Fig. 4. Extremely precarious shelter where waste pickers were living, inside the dumpsite.

We condemn the living conditions under which these people were living, but we do not blame them for being found in this situation; instead, we strongly encourage the local government to implement social programs that would generate income and employment for them. Our visit to Kachok confirmed the precarious sanitary conditions and environmental impacts that the dumpsite poses to Kisumu's population and biota, but it also unveiled social inequalities related to waste management that were not previously disclosed to us in our consultations.

When discussing possible solutions to substitute Kachok dumpsite, our key informants mentioned as possibilities landfill, anaerobic digestion (commonly referred to as 'biodigester' or 'biogas'), and incineration. There was some indication that a centralized waste management facility would be needed in the long term, but government officials seemed to promote the idea of decentralized Community Cookers, a low-cost waste-to-energy combustion technology that has been successfully implemented in other places in Kenya and allows communities or institutions to safely burn waste and, with the heat generated, cook food and boil water (UNFCCC 2021). Biodigestion pilot projects were also mentioned as having potential to be scaled up in the city. We visited one such pilot project in Kibuye market, where market organic waste was being transformed into biogas and fertilizer, which was applied in experimental agricultural plots. Another idea mentioned by our informants was the establishment of decentralized recovery centers, which could work as waste transfer stations and possibly waste sorting for recycling and some sort of waste-to-energy facility (either biodigesters or community cookers).

When asked about which factors were important to be considered in choosing the best waste treatment technology for Kisumu, our informants mentioned a range of aspects, as expected. Firstly, the technology should achieve its purpose of being able to treat the type of waste generated by Kisumu city (organic as the biggest fraction). It was mentioned that best available technologies should be assessed, but what works best in the local context was considered as equally important. Considering the nuisance and contamination resulting from the dumpsite, the environmental impacts of a new technology were also pointed out. It is important that by trying to solve one problem, another one is not created, therefore proper pollution control systems should be in place. Among the environmental concerns were soil, groundwater, and air pollution, as well as the rich ecosystem of Lake Victoria, already under pressure from other human activities. Cost effectiveness and affordability of the technology were other mentioned aspects, as well as public acceptance. During our conversations, the principle of 'zero waste' or 'minimum residue' was frequently mentioned, which meant that waste was not only meant to be buried or burned, but it should be transformed into useful byproducts, such as electricity or fertilizer. Waste-to-energy were also deemed desirable and useful as they would help addressing another challenge faced by Kisumu; that of universal access to electricity. Lastly, we showed the list of criteria that we had thought for our analysis and asked if they felt there was something missing. All key informants were happy with our suggestions and looked forward to the results of our study.

3.2. Analysis parameters: chosen technologies and criteria

In line with interview results, a review of Kenya's environmental policy made clear that waste-to-energy technologies ought to be encouraged and conditions for successful recycling of materials, expanded, confirming the views of our key informants. Kenya's National Solid Waste Policy is guided by the zero-waste principle, and sees waste as "a resource that can be harnessed to create wealth, employment and reduce pollution of the environment" (National Environment Management Authority 2014). One of the strategy's objectives is to promote resource recovery through recycling and energy generation, while allowing sanitary landfilling of inert waste (National Environment Management Authority 2014).

Anaerobic digestion, sanitary landfill, bioreactor landfill and incineration were the technologies chosen for this analysis, considering they are well established and can be implemented as large-scale plants. The technologies are briefly described below.

i. Anaerobic digestion (AD)

The organic fraction of municipal solid waste (OFMSW) can be treated in a biodigester to produce biogas and liquid and/or solid digestate (Roopnarain and Adeleke, 2017). Microorganisms break down organic matter in an anaerobic digestion process, in which 50 to 70% of the biogas generated is methane (R. Kigozi et al., 2014). The biogas can be used directly as fuel for cooking, heating or generating electricity, or it can be purified to serve as a fuel for transportation combustion engines, such as buses (Roopnarain and Adeleke, 2017). The resulting digestate is an organic nutrient-rich fertilizer that can be applied into agricultural soil (R. Kigozi et al., 2014), avoiding the use of chemical fertilizers.

ii. Sanitary landfill (SL)

Sanitary landfill is an engineered technique to dispose waste in the soil, paying attention to certain technical standards to guarantee site operation safety and environmental compliance (Forti et al., 2019). The most fundamental differences between a sanitary landfill and an open dumpsite are the soil sealing, by placing liners at the bottom and a daily cover of soil that enclose the waste; measures to avoid rainwater to reach the landfill; and leachate collection and treatment (Forti et al., 2019). The landfill gas generated can be released into the atmosphere without any control (similarly to open dumps), or it can be collected by a piping system and then flared (burned) to convert the methane into carbon dioxide, or to generate electricity (Mehta et al., 2018).

iii. Bioreactor landfill (BL)

Bioreactor landfills are built and operated in similar way to sanitary landfills, with the main difference being the recirculation of leachate, to increase the waste degradation rate (Hsiao, 2001). They can operate as an anaerobic, semi-aerobic (or hybrid) or aerobic bioreactor, in which air needs to be injected in order to create aerobic conditions (Ahmadifar et al., 2016). However, aerobic reactors demand additional costs with electricity and they can reduce the methane generation potential, consequently limiting the amount of energy that can be generated (Ahmadifar et al., 2016). The way bioreactor landfills are operated contribute to a faster settlement, and therefore allowing a more efficient use of the space than conventional landfills (Pacey et al., 1999). In anaerobic bioreactor landfills, the production of methane is increased in the first years of operation, making landfill gas-to-energy projects more economically feasible than in conventional landfills (Pacey et al., 1999).

iv. Incineration (IN)

Incineration is a highly technological waste treatment technique. It comprises the controlled combustion of waste in temperatures above 850 °C, which guarantees that all pathogens are killed (Lino and Ismail, 2018). The process significantly reduces waste volume and mass, while it produces carbon dioxide, heat to be converted to electricity, and ashes (Lino and Ismail, 2018). The bottom ash is biologically stable and can either be disposed of in hazardous waste landfills or used in the construction sector to build roads (Malakahmad et al., 2017). Incineration of MSW produces hazardous air pollutants that require advanced and costly treatment equipment in order to avoid human and environmental contamination (World Bank 1999, Yong et al., 2019).

In order to reflect the variety of concerns and priorities identified by us and our key informants and compare the different technologies, we selected a wide range of socioeconomic and environmental criteria, namely:

1. *Economic costs*: how cheap or expensive is each technology?
2. *Electricity generation potential*: how much electricity can be generated with each technology?
3. *Contribution to climate change potential*: how much greenhouse gas (GHG) emissions does each technology contribute to?
4. *Land footprint*: how much land is needed for each technology?
5. *Air pollution*: to what extent technologies degrade air quality?
6. *Soil and water contamination*: which technologies have higher risk of contaminating soil and water?
7. *Compatibility with source segregation and recycling efforts*: to what extent technologies need or allow segregation and recycling to be combined with the treatment solution?

The choice of criteria determined which keywords we used in our literature search and which data was collected from each reviewed article. The next section, dedicated to the multi-criteria analysis, was also defined by these criteria as we have structured our literature results presentation focusing on one criterion at a time. Each criterion is further explained in the next section, along with the results for each of them.

3.3. Multi-criteria analysis

3.3.1. Economic costs

We found the cost of waste treatment technologies to be a topic widely covered by the literature. It is a complex topic, since many factors influence the results, such as choice of technology, environmental control equipment installed and size of the facility, and which costs are considered in the calculations, e.g., if revenues from electricity sales (as cost abatement) or costs for land acquisition and post-closure phase are accounted for.

Most consulted articles differentiated **construction costs**, which are spent during the dozens of months needed to build the facility, from **operational costs**, which are yearly expenses dedicated to operating and maintaining the facility properly. In our results, we present those costs in two different forms: total and unitary.

Total construction cost is the total amount spent to build the facility, while **unitary construction cost** (also referred to as **CAPEX**) is obtained by dividing the total construction cost (US$) by the annual amount of waste treated (tonne/year). **Annual operational cost** is the amount spent every year to run the facility, while **annual unitary cost**

Table 3
Cost for Anaerobic Digestion.

Total construction cost (US$)	Annual operational cost (US$/year)	Annual amount of waste (tonne/year)	Unitary cost CAPEX (US$/(t/year))	Annual unitary cost OPEX (US$/tonne)	Location	Source
$ 826 237.46	$ 56 829.12	31 787	$ 25.99	$ 1.79	Zimbabwe	Sibanda et al., 2013
$ 6 500 000.00	–	45 359	$ 143.30	–	Kenya	Roopnarain and Adeleke, 2017
$ 12 050 000.00	–	111 474	$ 108.10	–	Brazil	d. Santos et al., 2019
-	$ 4 327 248.60	163 292	–	$ 26.50	China	Aleluia and Ferrão, 2017

Table 4
Costs for Sanitary Landfill.

Total construction cost (US$)				Unitary cost CAPEX (US$/(t/year))				
W/ flaring	W/ energy recovery	Annual amount of waste (tonne/year)	Total unitary project cost (US$/tonne MSW)	W/ flaring	W/ energy recovery	Annual unitary cost OPEX (US$/tonne)	Location	Source
$ 798 000.00		49 668	$ 16.07	–	–	$ 6.43	–	Zhang et al., 2011
-	–	116 800	$ 11.42	–	–	–	Saudi Arabia	Khan et al., 1987
$ 2 000 000.00	$ 5 000 000.00	120 000	–	$ 16.67	$ 41.67	–	–	Ayalon et al., 2000
-	–	132 200	$ 10.33	–	–	–	Saudi Arabia	Khan et al., 1987
-	–	173 557	$ 9.25	–	–	–	Malaysia	Chen et al., 2012
-	–	287 200	$ 8.06	–	–	–	Saudi Arabia	Khan et al., 1987

Table 5
Costs for Bioreactor Landfill.

Total construction cost (US$)	Annual amount of waste (tonne/year)	Total unitary project cost (US$/tonne MSW)	Location	Source
-	165 000	$ 37.00	–	Berge et al., 2009
$ 4 008 004.00	552 000	$ 7.26	India	Sivakumar Babu et al., 2014
-	–	$ 39.70	–	Cabaraban et al., 2008
-	–	$ 50.00	–	Cabaraban et al., 2008

Table 6
Costs for Incineration.

Total construction cost (US$)	Annual operational cost (US$/year)	Annual amount of waste (tonne/year)	Unitary cost CAPEX (US$/(t/year))	Annual unitary cost OPEX (US$/tonne)	Location	Source
$ 46 755 000.00	$ 2 209 613.00	68 039	$ 687.18	$ 32.48	Iran	Rezaei et al., 2018
$ 41 832 000.00	$ 1 974 000.00	124 647	$ 335.61	$ 15.84	China	Li et al., 2016
$ 21 460 728.19	$ 7 433 735.35	144 000	$ 149.03	$ 51.62	Indonesia	Sudibyo et al., 2017
$ 50 000 000.00	-	150 000	$ 333.33	-	–	Ayalon et al., 2000

(also referred to as **OPEX**) is obtained by dividing the annual operational cost (US$/year) by the annual amount of waste treated (tonne/year). For sanitary and bioreactor landfills, however, it was more common to find a different type of 'global' cost, the **total unitary project cost**, which follows the same logic of the abovementioned unitary costs, but without differentiating between construction and operational costs. This way of calculating the costs is not ideal, as the initial investment needed to build the facility gets diluted over the years of operation, and doesn't reflect well the spending reality.

Economic benefits and/or revenues from electricity sales, subsidies, carbon trade, etc. are highly variable and dependent on each country's policies, energy matrix and markets, and were therefore not considered in this exercise. Given that this is not an economic analysis and we are analyzing several other criteria, costs found in the literature were not converted to present values. Since the type of costs found for each technology varied, we first present results for each technology individually (Tables 3, 4, 5, 6) and then we compile them together in one table with value ranges and average unitary costs to facilitate comparison (Table 7).

According to Angenent et al. (2004), as cited in Manyi-Loh et al., 2019, anaerobic digestion does not use sophisticated equipment, and is less energy-intensive as aerobic processes; therefore, it is considered a lower cost option. However, our results show that it can be either a cheap or a more expensive option. For instance, Sibanda et al., 2013 estimated that the unitary initial investment for a plant in Harare, Zimbabwe, would be as low as US$26/(tonne MSW/year), while the annual operational costs would be as low as US$1.79/tonne MSW. But Aleluia and Ferrão, 2017 found that the annual operational costs in China were US$26.50/tonne MSW, 14 times higher than the value for Zimbabwe. Therefore, according to our comparison in Table 7, AD ranks 3rd place, being only cheaper than incineration, whose calculated average unitary costs are 2- to 4-times higher.

There is a consensus that landfilling techniques are extremely inexpensive when compared to high-tech incineration facilities (Hellweg et al., 2005, Maimone, 1985, Peerapong and Limmeechokchai, 2016, Thanh and Matsui, 2012), and this is confirmed by our results. According to Yong et al., 2019, an incinerator is 10-times more costly to build and three-times more costly to operate than a sanitary landfill. Landfilling becomes more expensive as environmental control activities are added, such as flaring and energy recovery (Mehta et al., 2018, Ayalon et al., 2000, Sivakumar Babu et al., 2014). The larger the landfill, the cheaper the cost per tonne of waste treated (Khan et al., 1987, Clarke, 2000).

According to Table 7, bioreactor landfills have similar cost ranges to sanitary landfill, but a higher average unitary cost. It makes sense to consider SL cheaper, where environmental control activities are optional, while in BL they are a requirement (otherwise the landfill does not operate as a bioreactor). We found contradictory arguments in that

Table 7
Unitary cost comparison between the four technologies.

Technology	Range of cost per tonne of waste (US$/tonne)		Average cost per tonne of waste (US$/tonne)		Rank (less expensive to more expensive)
	Unitary cost CAPEX (US$/(t/year))	Annual unitary cost OPEX (US$/tonne)	Average unitary CAPEX (US$/(t/year))	Average unitary OPEX (US$/tonne)	
AD	25.99 - 143.30	1.79 - 26.50	$ 92.46	$ 14.14	3
SL - No Landfill Gas Control		8.06 - 16.07		$ 1.02	1
SL - With Flaring	16.67	–	$ 16.67	-	1
SL - With Energy Recovery	41.67	–	$ 41.67	-	2
BL		7.26 - 50.00		$ 33.49	2
INC	149.03 - 687.18	15.84 - 51.62	$ 376.29	$ 33.31	4

regard. Warith et al., 2005 state that bioreactors are more costly than conventional landfills, while Pacey et al., 1999 argue that bioreactor landfills saves the costs of implementing new landfills (due to space recovery), treating leachate (due to leachate recirculation) and generates more revenues from higher electricity yields (due to accelerated degradation and earlier methane formation). Berge et al., 2009 show evidence that bioreactor landfills are economically equal or more advantageous than conventional ones, having found that US$1.83/tonne of waste is the additional cost for bioreactors, without accounting for savings from space recovery or leachate treatment (Gambelin et al. (1998), cited in Berge et al., 2009). We recognize that BL offer other, more 'strategic' advantages than SL, but taking into account a pure disbursement perspective, SL are ranked as cheaper than BL.

Incineration is the most expensive of all technologies according to our results, in line with the existing literature (Yong et al., 2019, Li et al., 2016, Maimone, 1985, Salvador et al., 2019). Peerapong and Limmeechokchai, 2016 state that, for developing countries, the cost of incineration is "prohibitively high" due to the costs of advanced technology and emissions control equipment, while Aleluia and Ferrão, 2017 found that higher processing capacities did not lead to lower operational costs.

3.3.2. *Electricity generation*

Electricity generation is another complex factor to compare across technologies, as the amount of electricity that can be generated depends not only on the amount of gas that is generated, but also its composition. Anaerobic processes tend to produce more methane, which is more easily converted into electricity or other forms of usable energy, than aerobic processes. The composition of the gas generated during waste decomposition also depends on the composition of the waste, but many other factors (such as the efficiency of collection of landfill gas). Waste-to-energy options were considered for electricity conversion only, and no production of heat. Due to Kenya's tropical climate, thermal energy for e.g., district heating, is not as important as electricity. Heat could be used by specific industries, but our analysis did not include the sale of heat in the calculation because of a lack of an established system in the region.

Table 8 displays the selected data from the literature for all four technologies, while in Table 9, we consolidated the unitary results into range and average values and ranked the options according to the highest electricity generation.

AD has the second-best electricity output among the four compared technologies. This is due to biogas produced in this process having high contents of methane, allowing the production of up to 418 kWh per tonne of waste (Sibanda et al., 2013). While only being able to receive organic waste can be seen as a limitation, it actually represents an advantage, as conversion of such a high moisture waste stream (such as food waste) is not feasible for other types of waste-to-energy technologies, where low moisture is desirable (Yong et al., 2019, Ogunjuyigbe et al., 2017, Murphy and McKeogh, 2004). Rupf et al., 2017 have shown that AD can reach increased methane yields if the organic fraction of MSW is co-digested along with other feedstocks, such as animal manure, sewage sludge or crop residues, thus augmenting the possibility of waste streams that can be treated in the same plant. Additionally, this technology is more versatile, as generation of electricity from biogas is only one among many options for energy recovery using AD (Roopnarain and Adeleke, 2017).

Landfills in general have the lowest energy recovery rate (Hellweg et al., 2005, Maimone, 1985), since landfill gas generation is diffuse and difficult to capture. In fact, the efficiency of the gas collection system dictates how much electricity can be produced from landfills and how much the facility contributes to global warming, in case of flaring (Broun and Sattler, 2016). Conventional landfills emit gas for longer periods of time (approximately 74 years, according to Broun and Sattler, 2016), but BL produce methane twice as fast as dry-tomb landfills (Hsiao, 2001) and earlier in the project life (Kumar et al., 2011), which can make landfill gas-to-energy projects more feasible (Benson et al., 2007). In theory, the amount of energy produced by SL and BL should not be very different, if all other variables are kept the same: although other authors found higher electrical outputs for SL, the values found by Broun and Sattler, 2016 were very low and similar, namely 3 kWh/tonne MSW for SL and 5 for BL. What is important to point out is that there is a lack of empirical data on BL's electricity production, thus making this technology rank 4th in this criterion. However, not all SL are equipped with energy recovery systems and, if they are, they tend to be more expensive. Nonetheless energy recovery in landfills should be encouraged as, despite increased costs, it provides an opportunity of revenue through selling electricity to the grid (Amini and Reinhart, 2011).

Incineration is undeniably the most efficient waste treatment technology in producing energy (Maimone, 1985, Aracil et al., 2018), which is confirmed by our results. Although the efficiency is higher when both electricity and heat are produced, producing only electricity is possible at lower efficiency rates, by cooling the surplus heat (World Bank 1999). This apparently excellent performance risk important waste stream requirements being neglected: incineration requires waste streams with high calorific values and low moisture, with a lower heating value (LHV) of at least 7 MJ/tonne MSW, to allow combustion without the addition of other fuels (Aleluia and Ferrão, 2017, Li et al., 2016). The World Bank 1999 adverts that overly wet waste streams in developing countries might not be suitable for combustion in incineration plants.

3.3.3. *Greenhouse gas emissions*

Our review showed that there is a growing body of literature concerning GHG emissions in recent years. However, we observed that there are many different methodologies to calculate them, which makes it harder to compare results across several studies. One common approach is to calculate emissions avoided (represented by negative values), for instance for substituting an open dump or landfilling scenario (Ayalon et al., 2000), or by avoiding burning of fossil fuels for electricity generation (Tolis et al., 2012). The problem with that approach is that results are always relative to the chosen scenario, and 'emissions avoided' tend to mask the real contribution of degradation of waste to climate change. Hence, for the purpose of this analysis, it makes more sense to compare the actual contribution to GHG emissions in absolute terms, not only potential relative savings. We have selected as

Table 8
Electricity generation for the four technologies.

Technology	Annual electricity generation (kWh)	Annual amount of waste (tonne)	Electricity generated per tonne of waste (kWh/tonne)	Location	Source
AD	3 369 529	16 424	205	South Africa	Masebinu et al., 2018
	13 280 400	31 787	418	Zimbabwe	Sibanda et al., 2013
	26 017 200	108 420	240	Brazil	Lino and Ismail, 2013
	20 097 000	111 474	180	Brazil	d. Santos et al., 2019
SL	2 741 202	44 925	61	Vietnam	Thanh and Matsui, 2012
	13 492 000	57 413	235	Sri Lanka	Menikpura et al., 2012
	–	821 848	297	Malaysia	Malakahmad et al., 2017
	–	–	102	Brazil	d. Santos et al., 2019
	–	–	3	USA	Broun and Sattler, 2016
BL	–	–	5	USA	Broun and Sattler, 2016
INC	10 680 000	30 000	356	Vietnam	Thanh and Matsui, 2013
	48 375 000	68 039	711	Iran	Rezaei et al., 2018
	20 216 409	125 997	160	Vietnam	Thanh and Matsui, 2012
	–	144 000	355	Indonesia	Sudibyo et al., 2017
	66 000 000	163 292	404	China	Li et al., 2016
	28 991 000	255 567	113	Brazil	Lino and Ismail, 2018

Table 9
Unitary electricity generation comparison between the four technologies.

Technology	Range of electricity generated per tonne of waste (kWh/tonne)	Average electricity generated (kWh/tonne)	Rank(higher avg generation to lower avg generation)
AD	180 - 418	261	2
SL	3 - 297	140	3
BL	5	5	4
INC	113 - 711	350	1

results only the data that brought information of calculated emissions by each technology; therefore ‘negative emissions’, when explicit, were excluded.

As a baseline, estimated emissions from open dumpsites give an idea of how much “better” each technology is at reducing emissions. Calculated emissions for dumpsites were 1.24 tonne CO_2eq/tonne MSW in Mumbai, India (Mehta et al., 2018); 1.21 tonne CO_2eq/tonne MSW in Bangkok, Thailand (Menikpura et al., 2013), and 0.73 tonne CO_2eq/tonne MSW in Kandy, Sri Lanka (Menikpura et al., 2012). As will be presented, values for landfilling of waste fall close to these values for open dumpsites, as the processes for degradation of waste in those options are similar.

Table 10 presents the unitary GHG emissions for all technologies, from different studies, taking into account different types of LFG control for SL, while Table 11 presents the comparison and ranking in terms of GHG emissions. Considering that the amount of GHG produced by degradation of waste will depend more on the degradation process than in the size of the plant, we have been more flexible in this criterion towards larger plants, or unitary results from studies that did not present the waste treating capacity.

Anaerobic digestion is considered a clean source of energy (Olugasa et al., 2014); our results confirm it as the technology that contributes the least to climate change, as also found by Malakahmad et al., 2017 and Murphy and McKeogh, 2004. Furthermore, there are studies that claim that AD avoids emissions of up to 1.391 t CO2eq/ tonne MSW (Ayalon et al., 2000).

Sanitary landfill is the largest GHG emitter among the evaluated alternatives (Aracil et al., 2018, Levis and Barlaz, 2011), and it can emit for 20–50 years after the landfill’s closure (Kamarrudin et al., 2013). According to Mehta et al., 2018, flaring of LFG can reduce the climate change impact of landfills in 32%. For fictitious scenarios in Vietnam, Thanh and Matsui, 2012 calculated that emissions from landfill without any control would be 1.14 tonne CO_2eq/tonne MSW, with flaring 0.035 tonne CO_2eq/tonne MSW (97% reduction) and with energy recovery 0.008 tonne CO_2eq/tonne MSW (99% reduction). Emission values from the literature are slightly lower for SL with energy recovery than for flaring; however, we have ranked those options to be equally performing, as waste is degraded in the same way and LFG is converted from methane to carbon dioxide. In addition, Broun and Sattler, 2016 have found that the LFG collection efficiency significantly influences the net emissions from landfills, as it dictates how much fugitive methane emissions will be emitted during the life cycle of the landfill. Hence, from a climate perspective, it is essential to implement efficient landfill gas control systems when building new sanitary landfills, even if energy recovery is not in place.

Bioreactor landfills are believed to emit fewer greenhouse gasses than conventional landfills (Kumar et al., 2011, Ghosh et al., 2019) since they are designed and operated with the aim of collecting LFG more efficiently (Di Maria et al., 2016). Manfredi and Christensen, 2009 recognize that bioreactor landfills reduce the time frame from 40 to 15 years in which landfill gas can be extracted, although from a life cycle perspective of 100 years, the global warming impact of bioreactors is similar to that of sanitary landfills. However, our results indicate higher values and, once again, the limited quantitative data available for bioreactor landfills has made this technology score lower in our ranking. It is important to notice though, that bioreactor landfills should have similar climate change contribution performance to SL with LFG control.

Incineration tends to perform well in GHG emissions, as studies often count the high energy output as carbon offsets which reduce the overall impact of the activity (Thanh and Matsui, 2013, González et al., 2018, Autret et al., 2007). However, our results have shown that incineration’s emissions are higher than those arising from AD, making this technology rank as the 2nd highest for this criterion.

3.3.4. Land footprint

This criterion concerns the amount of land required to build and operate the waste treatment facilities, in square meters (m^2). Although quite straightforward, this was not an aspect widely covered by the consulted literature and our analysis is thus limited. The importance of this criterion lies in the costs for land acquisition, as well as in finding large enough available land within a reasonable distance, to avoid burdening transportation costs. Apart from the economic aspect, less land also

Table 10
GHG emissions for the four technologies, with 3 types of LFG control for SL.

Technology	Total annual emissions (t CO2eq)	Annual amount of waste (tonne)	Emissions per tonne of waste (t CO2eq/ tonne MSW)	Location	Source
AD	7 950	108 420	0.073	Brazil	Lino and Ismail, 2013
	–	–	0.251	Malaysia	Malakahmad et al., 2017
SL - No Landfill Gas Control	110 896	346 045	0.320	Brazil	Lino and Ismail, 2018
	–	–	1.100	–	Levis and Barlaz, 2011
	46 457	40 755	1.140	Vietnam	Thanh and Matsui, 2012
	–	1 277 500	1.370	Thailand	Menikpura et al., 2013
SL - With Flaring	1 404	40 755	0.034	Vietnam	Thanh and Matsui, 2012
	18 620	346 045	0.054	Brazil	Lino and Ismail, 2018
	30 726	300 000	0.102	Iraq	Mustafa et al., 2013
	–	–	0.209	Sri Lanka	Menikpura et al., 2012
	–	821 848	0.412	Malaysia	Malakahmad et al., 2017
	–	–	0.844	India	Mehta et al., 2018
	–	–	1.075	–	Levis and Barlaz, 2011
SL - With Energy Recovery	324	40 755	0.008	Vietnam	Thanh and Matsui, 2012
	–	821 848	0.110	Malaysia	Malakahmad et al., 2017
	–	–	0.209	Sri Lanka	Menikpura et al., 2012
	–	1 277 500	0.728	Thailand	Menikpura et al., 2013
	–	–	0.860	–	Levis and Barlaz, 2011
BL	–	–	0.300	Italy	Di Maria et al., 2016
	–	–	0.803	USA	Broun and Sattler, 2016
	–	–	1.540	–	Cabaraban et al., 2008
INC	–	194 150	0.124	Ireland	Murphy and McKeogh, 2004
	16 890	108 420	0.156	Brazil	Lino and Ismail, 2013
	–	–	0.210	USA	Coventry et al., 2012
	84 303	255 567	0.330	Brazil	Lino and Ismail, 2018
	114 100	281 715	0.405	Brazil	Lino and Ismail, 2017
	–	–	0.646	Malaysia	Malakahmad et al., 2017

Table 11
Unitary GHG emissions comparison between the four technologies.

Technology	Range of emissions per tonne of waste (t CO2eq/ tonne MSW)	Average emissions per tonne of waste (t CO2eq/ tonne MSW)	Rank (lower avg emissions to higher avg emissions)
AD	0.073 - 0.251	0.162	1
SL - No Landfill Gas Control	0.320 - 1.370	0,983	4
SL - With Flaring	0.034 - 1.075	0,390	3
SL - With Energy Recovery	0.008 - 0.860	0,383	3
BL	0.300 - 1.540	0.881	4
INC	0.124 - 0.646	0.312	2

Table 12
Land footprint for the four technologies.

Technology	Annual amount of waste (tonne)	Total area (m^2)	Area per tonne of waste (m^2/tonne)	Location	Source
AD	50 000	10 000	0.20	–	Murphy and McKeogh, 2004
	100 000	15 000	0.15	–	Murphy and McKeogh, 2004
SL	54 431	550 000	10.10	Sweden	Hsiao, 2001
	155 100	257 000	1.66	Brazil	Lino and Ismail, 2013
	173 557	500 000	2.88	Malaysia	Chen et al., 2012
	200 000	360 000	1.80	Poland	Jakubiak, 2014
BL	109 000	97 000	0.89	USA	Benson et al., 2007
	116 000	36 000	0.31	USA	Benson et al., 2007
	165 000	134 000	0.81	–	Berge et al., 2009
INC	226 795	454 500	2.00	Netherlands	Maimone, 1985

means less environmental impacts (Manyi-Loh et al., 2019). Table 12 brings the total areas found for each technology, as well as the calculated unitary area per tonne of waste, while Table 13 presents the comparison between the four technologies.

Anaerobic digestion requires limited amount of land, due to operations needing high organic load rates and no oxygen (Malakahmad et al., 2017, Manyi-Loh et al., 2019), and this is also reflected in our results. Since biodigesters are equivalent to tanks, it was also common to find reference to the volume of biodigesters rather than the surface area they occupy, such as in R. Kigozi et al., 2014 and Bauer, 2018.

Again, landfills score poorly in this category, being the worst ranked in our analysis. According to Maimone, 1985, sanitary landfills can take more than twice the land area needed for other treatment options, but our results show that it can be up to 50 times more than AD, and 5 times more than for INC. The amount of land needed for landfilling is an issue due to unavailability of land in urbanizing areas of certain countries (Manyi-Loh et al., 2019), the loss of property values in the nearby area (Hirshfeld et al., 1992), the likely social unacceptance by future neighbors and eventual need for relocation or resettlement of families or activities (Mato, 1999).

Table 13
Unitary land footprint comparison between the four technologies.

Technology	Range of area occupied per tonne of waste (m^2/tonne)	Average area occupied per tonne of waste (m^2/tonne)	Rank (lower avg area to higher avg area)
AD	0.15 - 0.20	0.18	1
SL	1.66 - 10.10	4.11	4
BL	0.31 - 0.89	0.67	2
INC	2.00	2.00	3

Table 14
Air pollutant emissions for sanitary landfill, bioreactor landfill and incineration.

Tech-nology	PM emissions (g/tonne)	CO emissions (g/tonne)	NO_x emissions (g/tonne)	SO_x emissions (g/tonne)	HCl emissions (g/tonne)	Dioxins emissions (g/tonne)	HF emissions (g/tonne)	H_2S emissions (g/tonne)	Location	Source
SL	3.20	89.13	53.08	10.14	5.56	7.55×10^{-8}	0.86	12.65	China	Li et al., 2015
	2.60	529	512.40	–	–	–	–	–	USA	Broun and Sattler, 2016
	20	–	245	180	–	–	–	–	Italy	Di Maria et al., 2016
BL	2.50	477.60	462.70	–	–	–	–	–	USA	Broun and Sattler, 2016
	12.50	–	261	134	–	–	–	–	Italy	Di Maria et al., 2016
INC	108.45	394.60	789.20	394.52	174.40	3.95×10^{-7}	–	–	China	Li et al., 2015

Table 15
Air quality impact comparison between the four technologies.

Technology	Rank (lower impact to higher impact)
AD	1
SL	3
BL	2
INC	4

Bioreactor landfills' improved operations also aim at reducing land footprint. The rapid settlement of bioreactors allows more waste to be deposited in the landfill airspace (Pacey et al., 1999, Benson et al., 2007). Warith (2002), as cited in Kumar et al., 2011, found that the gain in landfill space is estimated between 15–30%. Our results show such a good performance that BL are scoring 2nd best, more than incineration, although those results might be influenced by the small size of the bioreactor cells currently in operation and the lack of data on land used by incinerators.

Our results suggest that incineration require larger facilities than AD and BL, but, although requiring large plants, the advantage of incineration lies in the reduction of original volume of wastes by 80–95% (Thanh and Matsui, 2012, Luoranen and Horttanainen, 2007).

3.3.5. *Air pollution*

The degradation of waste can release much more than only carbon dioxide and methane, and that is why we have a separate criterion for the impact on air quality. This criterion also becomes complex as we cannot extensively cover all air pollutants within the scope of this analysis. Therefore, we present a few selected pollutants, namely particulate matter (PM), carbon monoxide (CO), nitrogen oxides (NO_x), sulfur oxides (SO_x), hydrochloric acid (HCl), dioxins, hydrogen fluoride (HF) and hydrogen sulfide (H_2S), for SL, BL and INC in Table 14 and the rank comparison based on quantitative and qualitative data in Table 15. Calculating average values from such a small dataset for so many different pollutants would add little to our analysis. Therefore, to build the rank for air quality impact, we considered the overall number of pollutants and level of emissions of each technology, as well as other qualitative data found on the literature.

Anaerobic digestion is considered a clean source of energy (Salvador et al., 2019); no quantitative data regarding air pollution from AD was found in our consulted literature. According to Manyi-Loh et al., 2019, AD processes reduce production of unpleasant odors.

Landfill gas contains non-methane organic compounds (NMOCs), hydrogen sulfide (H_2S), Nitrogen Oxides (NO_x), Sulfur Oxides (SO_x), heavy metals and others (Kamarrudin et al., 2013, Hirshfeld et al., 1992, Li et al., 2015). Among NMOCs, there are volatile organic compounds (VOCs) such as benzene, toluene, ethylbenzene and xylenes (BTEX) which pose risk to human health (Kamarrudin et al., 2013). Emissions from landfills can be point source, from flaring and electricity generation chimneys, and diffuse from the site (Li et al., 2015), including dust and soil movement from operations of machines (Hirshfeld et al., 1992). Although landfill's air quality impact is not trivial, it is scoring 3rd in our ranking, before incineration.

In theory, bioreactor landfills have similar air pollution performance than SL, but our results have found less pollutants, which can also be explained by the lack of data for this technology. According to Broun and Sattler, 2016, bioreactor landfills have a better performance than landfills in NO_x and CO emissions.

Incineration poses the biggest risk when it comes to air pollution (Manyi-Loh et al., 2019), ranking as the worst technology in our analysis. Apart from SO_x, NO_x, Hydrofluoric acid (HF), dust and heavy metals (Li et al., 2015, Costi et al., 2004), dioxins are formed during incineration and represent a risk to human health (Maimone, 1985). Both landfilling and incineration also emit Ozone (O_3), which contributes to smog formation, and CFCs, which are substances that deplete the ozone layer (Coventry et al., 2012). Advanced air pollution control equipment exists and is required for carrying out incineration activities safely (Coventry et al., 2012, Bidart et al., 2013). If air pollutants from incineration activities are not filtered or accidentally leak into the environment, there can be long-term impacts in the environment and the people living nearby (Yong et al., 2019). The World Bank 1999 alerts to the fact that the adoption of expensive pollution control equipment can depend on national air quality regulations, i.e., if developing countries do not have stringent regulations for incineration emissions, this can pave the way to not adopting such equipment control and thus putting society and the natural environment at risk.

3.3.6. *Soil and water contamination*

The risk of contamination of soil and surface or groundwater is another important environmental impact associated with solid waste treatment and disposal. In our literature sample, this topic was covered more

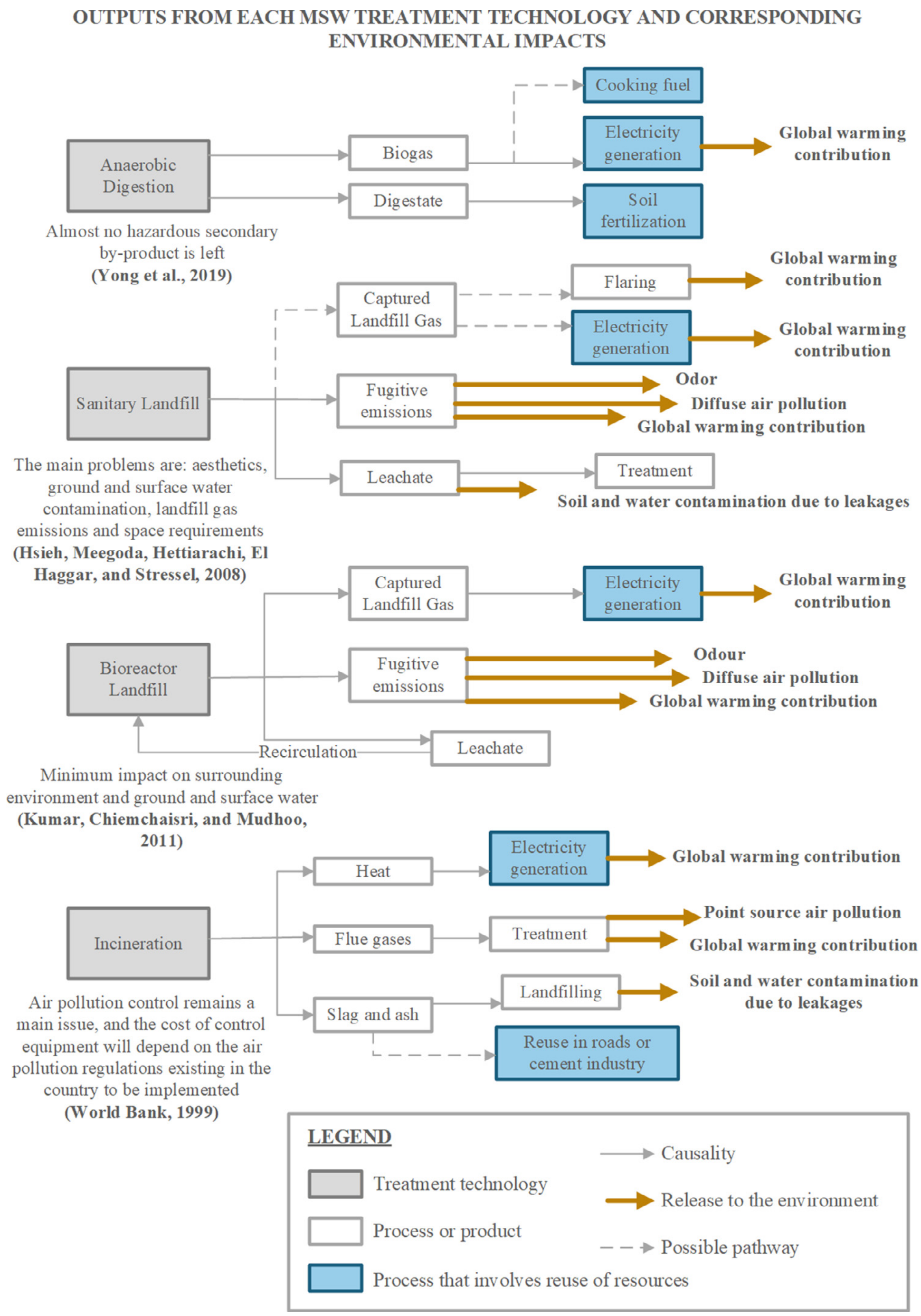

Fig. 5. Summarized qualitative environmental impacts and risks for the four technologies.

in qualitative rather than quantitative ways. It is also a difficult criterion to compare quantitively, since (i) the liquid and solid products and associated pollutants largely vary across technologies, (ii) actual contamination of soil and water bodies depend on many reasons, but mainly accidental releases to the environment, (iii) on-site monitoring results need to be compared to baseline data in order to assess contamination, and (iv) permissible levels of pollutants released to the environment based on national or international regulations can vary significantly. Moreover, our review showed that soil and water contamination is more a *risk* than an impact.

Our results for this criterion are presented in Fig. 5, a diagram that summarizes the environmental impacts arising from each technology, namely the contribution to global warming (by the emission of greenhouse gasses), emissions of odor and air pollutants (either as a source point or in a diffuse manner), contamination of soil and water due to leakages, and the possible beneficial processes that involve reuse of resources, in blue, which are electricity generation from gasses generated and captured in the waste decay process, the generation of cooking fuel (biogas), the production of soil fertilizer (digestate), and the reuse of incineration slag for construction purposes. Then, Table 16 displays the ranking for the four technologies in terms of water and soil contamination.

Anaerobic digestion ranks the highest, since the liquid output (digestate) can be used to improve soil fertility (Andreazzi et al., 2017) and leaves no hazardous product which could contaminate soil or water (Yong et al., 2019). In fact, according to Levis and Barlaz, 2011, AD is the best performing technology in environmental terms.

Sanitary landfill is the technology of greatest concern when it comes to the risk of soil and water contamination. The way landfills are designed aims at reducing those risks, but they will always threaten surface

Table 16
Soil and water contamination risk comparison between the four technologies.

Technology	Rank (lower risk to higher risk)
AD	1
SL	4
BL	3
INC	2

Table 17
Compatibility with recycling efforts comparison between the four technologies.

Technology	Rank (higher compatibility to lower compatibility)
AD	1
SL	3
BL	2
INC	4

and groundwater quality (Hirshfeld et al., 1992, Ahmad and Jani, 2018). Leachate is rich in nutrients and toxic compounds, such as heavy metals, ammonia and other organic substances (Malakahmad et al., 2017). Production of leachate will continue for years after the landfill is closed, requiring leachate collection and groundwater monitoring to go on for many decades (Ahmad and Jani, 2018, Madon et al., 2019, Salleh and Hamid, 2013). Malakahmad et al., 2017 calculated that Jeram Sanitary Landfill in Malaysia produces 0.188 m^3 of leachate per tonne of MSW disposed. Awaz, 2015 found sulfate, phosphate, nitrate, nickel and manganese levels above WHO permissible limits in groundwater surrounding a landfill in Kirkuk, Iraq. High values of biochemical organic demand (BOD) and chemical organic demand (COD), water quality parameters used for measuring organic matter content, also proved that leachate had contaminated the groundwater (Awaz, 2015). Tanjung Dua Belas Sanitary Landfill in Malaysia had groundwater samples with ammoniacal nitrogen and total dissolved solids above benchmark levels and high concentrations of lead, cadmium, copper and manganese (Ahmad and Jani, 2018). Xu (1998) apud Clarke, 2000 calculated the environmental cost of the risk of groundwater contamination as being US$1/tonne of waste disposed. The abovementioned figures are not extensive and only represent a few examples of the evidence found in landfill's impact on soil and groundwater quality.

Bioreactor landfills have a better environmental performance than conventional landfills (Hsiao, 2001). Instead of requiring expensive treatment, the leachate is recirculated into the landfill, contributing to the transformation of organic and inorganic components, and even reducing the concentration of heavy metals (Ahmadifar et al., 2016, Pacey et al., 1999). According to Pohland (1995) apud Pacey, et al. (Pacey et al., 1999), leachate recirculation promotes processes such as filtration, capture, sorption, precipitation and dehalogenation, removing pollutants. This means that bioreactor landfills have a lower risk of impacting surface and groundwater, including during the post-closure phase, when compared to sanitary landfills (Kumar et al., 2011, Méry and Bayer, 2005).

The process of waste incineration leaves a solid slag, or bottom ash, as residue (World Bank 1999, Autret et al., 2007). The amount of ash left depends on the composition of the incinerated waste, but it can range from 100 to 300 kg/tonne of MSW (Malakahmad et al., 2017, Autret et al., 2007). Incineration plants also produce residues from flue gas cleaning processes (World Bank 1999). Both residues have to be sent to hazardous waste landfills for final disposal, but the ashes can also be used for building roads or in the cement industry (Lino and Ismail, 2018, Malakahmad et al., 2017, World Bank 1999, Li et al., 2015). This means that incineration has an indirect risk of contaminating soil and water from disposing its residues in landfills. Although hazardous, we have deemed the risk of contamination due to incineration to be less than for SL and BL, since the volume of ash is only a fraction of the initial MSW, thus requiring much smaller landfills.

3.3.7. Compatibility with segregation at source and recycling

The compatibility with segregation at source and recycling relates to the whole municipal solid waste management system, meaning that a desirable technology would fit a system where recycling is a priority. Although a less conventional criterion, we deemed important to include it in our assessment since many people rely on recycling as a livelihood in Kisumu, and the local government expressed their interest in expanding it. This is also in line with current Kenyan policies, as described in Section 3.2. In order to assess this criterion, we examined the literature to find intrinsic characteristics of the assessed technologies that would require or benefit from waste segregation before treatment. Table 17 presents the results of our analysis, the rank comparison between the four technologies.

Anaerobic digestion ranks first as a program of source segregation is imperative for it to function. AD can only treat organic waste, being a suitable technology for places that produce significant amounts of wet MSW, such as food waste (Yong et al., 2019). If effectively implemented and managed, a segregation system at source combined with AD would have the potential to contribute to a circular economy on multiple fronts, such as materials recovery for new products, organic soil fertilizer production and climate-friendly energy conversion.

Neither sanitary landfill nor bioreactor landfill require segregation at source. However, they are compatible with recycling programs, as that follows the waste hierarchy and saves up landfill space. Therefore, segregation at source and recycling can be regarded as optional, but beneficial for landfills. Bioreactor landfills can be mined for material recovery and recycling after their lifetime is over. This "sustainable landfill" technique is, however, still under development (Hsieh et al., 2008). Hence, BL ranks second and SL ranks third in this criterion.

Incineration is controversial when it comes to waste segregation. Energy recovery is maximized as electricity and heat are produced (Xin-gang et al., 2016), but that is better achieved for unsegregated waste with a low moisture content and high calorific value (Aleluia and Ferrão, 2017). Furthermore, the World Bank 1999 cautions that incineration has potential negative impacts on informal recycling activities, which is a major livelihood for vulnerable lower-income population. In order to try to curb those negative effects, waste pickers might act earlier in the waste chain, changing the waste stream's combustibility (World Bank 1999). If waste segregation at source is in place, then the "true waste" that remains to be combusted might be insufficient to sustain an incinerator.

3.3.8. Overall results of multi-criteria analysis

After having analyzed four waste treatment technologies for seven socioeconomic and environmental criteria, we present the results of our rankings in one combined MCA matrix (Table 18). The numbers 1, 2, 3, 4 are the same as presented in the previous sections, this table is simply a compilation of all gradings to support visualization of strengths and weaknesses of each technology and enable comparison between them.

3.4. Recommendations for Kisumu

The choice of an optimal treatment technology for Kisumu will depend on what is more important and for whom, not to mention hidden or explicit political interests and power relations. To allow flexibility in using the results of our research, our analysis did not attribute weights to each criterion, leaving it to decision-makers to take into account different views and voices from the public and decide on a desired treatment technology for the city. We do, however, share our recommendations for Kisumu, in the hope that we have a more "neutral" perspective as researchers.

According to the finding in Table 18, anaerobic digestion is the technology that collects more advantages over the other three, being the

Table 18
Multi-criteria analysis for the four technologies.

Criteria	Anaerobic digestion	Sanitary landfill			Bioreactor landfill	Incineration
		no LFG control	w/ flaring	w/ energy recovery		
1. Cost	3	1	1	2	2	4
2. Electricity	2	–	–	3	4	1
3. GHG	1	4	3	3	4	2
4. Land	1	4	4	4	2	3
5. Air quality	1	3	3	3	2	4
6. Soil/water	1	4	4	4	3	2
7. Recycling	1	3	3	3	2	4

most environmentally sound technology, the second best at generating electricity and the third cheapest option. AD could convert the organic fraction, which accounts for 63% of the waste generated in the city, into a usable form of energy and fertilizer. There are potential synergies between implementing AD in conjunction with an augmented material recycling system in Kisumu, in order to ensure that the organic waste stream arrives at the digester free from inorganic materials and other pollutants. Furthermore, AD is a flexible system and could be implemented in the city as one large digester, or it could consist of several de-centralized digesters (e.g. at food markets), which could save waste transportation costs and related greenhouse gas emissions.

Either sanitary or bioreactor landfill would represent an improvement from Kisumu's current open dumping situation. Landfilling waste is gradually becoming a less preferred technology for treating municipal solid waste due to the heavy environmental burdens and liabilities that last for many decades. But it is often adopted by low and middle-income countries as a less-expensive alternative to mitigate impacts from open dumping. Challenges for Kisumu, regarding landfilling options, would be finding available land and its distance to main waste generators, similarly to what happened with previous failed attempts of relocating Kachok (Awuor et al., 2019). Meeting existing expectations of generating energy from waste would be another challenge, as conversion efficiency would be low, and LFG-to-energy equipment would increase the project's cost.

The potential challenges posed by the possibility of installing an incinerator in Kisumu are probably more concerning than those for landfills. In order to make the plant safe, expensive air quality control would need to be in place, which could make the project economically not feasible. The high moisture content of Kisumu's waste poses a technical challenge for incineration due to reduced combustibility of the waste generated in the city's households. During our fieldwork, we have observed that plastic bottles are one of the biggest targets for recycling by waste pickers and recyclers, and incineration could negatively impact their livelihoods. An incineration plant would probably attempt to incinerate plastics to increase the waste stream's combustibility, which could lead to an unfair competition with the vulnerable population that depends on this material for earning income.

The government of Kisumu has, therefore, the responsibility and possibility to not only solve the 'dumpsite crisis' by implementing an economically feasible and environmentally sound technology such as anaerobic digestion, but also to maximize the social benefits from it, by expanding its recycling system, including waste pickers, and alleviating poverty. The proper segregation of organic waste from other materials is also fundamental to ensuring smooth operations of anaerobic digestion, and we see this as an opportunity to better engage Kisumu's population in waste sorting and increase environmental awareness.

4. Conclusion

In this study we have discussed the advantages and disadvantages of four solid waste treatment technologies and provided recommendations for Kiumu, Kenya. Our results and recommendations are tailored for Kisumu's case, but they can be relevant for researchers and policymakers elsewhere, especially from cities in low and middle-income countries facing similar challenges. We found that anaerobic digestion would be a suitable solution for Kisumu, due to its potential of generating electricity and reduced environmental impacts, not to mention compatibility with recycling and suitability to the city's significant organic waste stream. Municipal authorities in Kisumu can implement policies that combine resource recovery with social inclusion. However, additional research is needed on technical and economic feasibility of the technology, potential location of facilities, solid waste collection and segregation systems, and inclusion of waste pickers.

Authors' contributions

All authors contributed to the study conception and design. Data collection, treatment and analysis were performed by LCM. The first draft of the manuscript was written by LCM and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix: Interview guide

1) What are the current challenges regarding Solid Waste Management in the region?
   a Short term?
   b Long term?
2) What relevant treatment technologies do you know of that could be implemented in Kisumu?
3) What factors or criteria would in you consider in choosing a waste disposal technology? Short/long term?
4) What environmental parameters are important for us to consider in our analysis?
5) How does legislation influences the choices on SWM? What is the relevant legislation concerning air pollution? What air pollutants are regulated?
6) How likely will the municipality be able to implement household waste separation? (That's fundamental for our alternatives to be successful)

7) Governance: how should the facilities be managed and who should own them? What should be the level of government involvement in that system?

References

Ahmad, M.H., Jani, J., 2018. Comparison of groundwater quality status at active and inactive landfill in Selangor, Malaysia. International Journal of Civil Engineering and Technology 9 (7), 1896–1902. http://www.iaeme.com/ijciet/issues.asp?JType=IJCIET&VType=9&IType=7.

Ahmadifar, M., Sartaj, M., Abdallah, M., 2016. Investigating the performance of aerobic, semi-aerobic, and anaerobic bioreactor landfills for MSW management in developing countries. J. Mater. Cycles Waste Manage. 18 (4), 703–714. doi:10.1007/s10163-015-0372-0.

Aleluia, J. and Ferrão, P., Assessing the costs of municipal solid waste treatment technologies in developing Asian countries, Waste Manage. 69 (2017) 592–608. https://doi.org/10.1016/j.wasman.2017.08.047.

Amini, H.R., Reinhart, D.R., 2011. Economic benefits from landfill gas to energy production. Proceedings of the Air and Waste Management Association's Annual Conference and Exhibition 2005–2009.

Andreazzi, M.A., Mendes, A.R., d. Oliveira, K.V., d. l. A. P. Lizama, M., 2017. Energy management: a synthesis of scientific publications on biodigestion for waste management. Revista Ambiente & Água 12, 964–972 http://www.scielo.br/scielo.php?script=sci_arttext&pid=S1980-993x2017000600964&nrm=iso.

Aracil, C., Haro, P., Fuentes-Cano, D., and Gómez-Barea, A., Implementation of waste-to-energy options in landfill-dominated countries: Economic evaluation and GHG impact, Waste Manage. 76 (2018) 443–456. https://doi.org/10.1016/j.wasman.2018.03.039.

Autret, E., Berthier, F., Luszezanec, A., Nicolas, F., 2007. Incineration of municipal and assimilated wastes in France: Assessment of latest energy and material recovery performances. J. Hazard. Mater. 139 (3), 569–574. doi:10.1016/j.jhazmat.2006.02.065.

Awaz, B.M., 2015. Leachate and ground water assessment at Kirkuk sanitary landfill site in Zindana village, Iraq. International Journal of Environmental Research 9 (2), 457–466. https://ijer.ut.ac.ir/article_918_d8c88f7e9f98be062655fbce77b117d9.pdf.

Awuor,F.O., Nyakinya, B., Oloo, J., Oloko, M., and Agong', S.G., How Did Kachok Dumpsite in Kisumu City Develop into a Crisis?, Urban Forum 30(1) (2019) 115–131. https://doi.org/10.1007/s12132-018-9342-7.

Ayalon, O., Avnimelech, Y., Shechter, M., 2000. Alternative MSW treatment options to reduce global greenhouse gases emissions - the Israeli example. Waste Manage. Res. 18 (6), 538–544. doi:10.1177/0734242x0001800604.

Bauer, W., 2018. Turning Waste into Power: Michigan State University's Anaerobic Digester. In: Leal Filho, W., Frankenberger, F., Iglecias, P., Mülfarth, R.C.K. (Eds.), Towards Green Campus Operations: Energy, Climate and Sustainable Development Initiatives at Universities. Springer International Publishing, Cham, pp. 385–391.

Benson, C.H., Barlaz, M.A., Lane, D.T., Rawe, J.M., 2007. Practice review of five bioreactor/recirculation landfills. Waste Manage. 27 (1), 13–29. doi:10.1016/j.wasman.2006.04.005.

Berge, N.D., Reinhart, D.R., and Batarseh, E.S., An assessment of bioreactor landfill costs and benefits, Waste Manage. 29(5) (2009) 1558–1567. https://doi.org/10.1016/j.wasman.2008.12.010.

Bidart, C., Fröhling, M., Schultmann, F., 2013. Municipal solid waste and production of substitute natural gas and electricity as energy alternatives. Appl. Therm. Eng. 51 (1), 1107–1115. doi:10.1016/j.applthermaleng.2012.10.021.

Broun, R., Sattler, M., 2016. A comparison of greenhouse gas emissions and potential electricity recovery from conventional and bioreactor landfills. J. Cleaner Prod. 112, 2664–2673. doi:10.1016/j.jclepro.2015.10.010.

Cabaraban, M.T.I., Khire, M.V., Alocilja, E.C., 2008. Aerobic in-vessel composting versus bioreactor landfilling using life cycle inventory models. Clean Technol. Environ. Policy 10 (1), 39–52. doi:10.1007/s10098-007-0125-4.

Chen, Z., Chenayah, S., Hamid, F.S., 2012. Environmental Evaluation of Sanitary Landfills Establishment: Malaysian Case Studies. In: Cheng, S., Zhang, G. (Eds.), Advances in Environmental Engineering. Trans Tech Publications Ltd, Durnten-Zurich.

Clarke, W.P., 2000. Cost-benefit analysis of introducing technology to rapidly degrade municipal solid waste. Waste Manage. Res. 18 (6), 510–524. doi:10.1177/0734242x0001800602.

Costi, P., Minciardi, R., Robba, M., Rovatti, M., and Sacile, R., An environmentally sustainable decision model for urban solid waste management, Waste Manage. 24(3) (2004) 277–295. https://doi.org/10.1016/S0956-053X(03)00126-0.

County Government of Kisumu, Kisumu Integrated Solid Waste Management Plan (KISWaMP) by horizon 2030. 2017.

Coventry, Z., Tize, R., Karunanithi, A., 2012. Environmental life-cycle assessment of waste-to-energy technologies. In: Air and Waste Management Association—International Conference on Thermal Treatment Technologies and Hazardous Waste Combustors17-19 May, pp. 159–174.

d. Santos, R.E., d. Santos, I.F.S., Barros, R.M., Bernal, A.P., Tiago Filho, G.L., d. G. B. d. Silva, F., 2019. Generating electrical energy through urban solid waste in Brazil: An economic and energy comparative analysis. J. Environ. Manage. 231, 198–206. doi:10.1016/j.jenvman.2018.10.015.

Di Maria, F., Micale, C., Sisani, L., Rotondi, L., 2016. Treatment of mechanically sorted organic waste by bioreactor landfill: Experimental results and preliminary comparative impact assessment with biostabilization and conventional landfill. Waste Manage. 55, 49–60. doi:10.1016/j.wasman.2016.03.033.

Forti, J.C., Lima, P.G., Reis, A.R., dos Santos, F.A., Braga Junior, S.S., 2019. Analysis of heavy metals and aromatics compounds in soil layers of a sanitary landfill. Environ. Qual. Manage. 28 (3), 123–130. doi:10.1002/tqem.21607.

Ghosh, A., Sarkar, J.P., Das, B., 2019. Sustainable Energy Recovery from Municipal Solid Waste (MSW) using Bio-reactor Landfills for Smart City Development. In: 2019 IEEE International Conference on Sustainable Energy Technologies and Systems (ICSETS), pp. 242–246.

González, P., Riveros, S., Concha, S., Casas, Y., 2018. Waste-to-energy options within a circular economy strategy in a developing country: the case of the bio bio region in Chile. International Journal of Energy Production and Management 3 (2), 144–156. doi:10.2495/EQ-V3-N2-144-156.

Gutberlet, J., Kain, J.-H., Nyakinya, B., Ochieng, D.H., Odhiambo, N., Oloko, M., Omolo, J., Omondi, E., Otieno, S., Zapata, P., Zapata Campos, M.J., 2016. Socio-environmental entrepreneurship and the provision of critical services in informal settlements. Environment & Urbanization 28 (1), 205–222. doi:10.1177/0956247815623772.

Hellweg, S., Doka, G., Finnveden, G., Hungerbühler, K., 2005. Assessing the Eco-efficiency of End-of-Pipe Technologies with the Environmental Cost Efficiency Indicator. J. Ind. Ecol. 9 (4), 189–203. doi:10.1162/108819805775247864.

Hirshfeld, S., Vesilind, P.A., Pas, E.I., 1992. Assessing the True Cost of Landfills. Waste Manage. Res. 10 (6), 471–484. doi:10.1177/0734242x9201000602.

Hsiao, K.-L., 2001. An Environmental Evaluation of Landfill Systems - Case Study from Two Landfills in South Sweden. Master of Science in Environmental Science), Lund University, Lund, Sweden.

Hsieh, H.N., Meegoda, J.N., Hettiarachi, J.P.A., El Haggar, S., Stressel, R.I., 2008. Towards the Development of Sustainable Landfills. GeoCongress 2008. Geotechnics of Waste Management and Remediation 344–351.

Jakubiak, M., 2014. Analysis of Implementing Sustainable Municipal Solid Waste management. Krakow city Case Study.

Kamarrudin, N., Zulkafli, N.H., Sikirman, A., Mahayuddin, N.M., Sigau, B.A., Hamid, K.H.K., Akhbar, S., 2013. Concentration and toxicological study on sanitary landfill gases at drilling point closed cell. In: 2013 IEEE Business Engineering and Industrial Applications Colloquium (BEIAC), pp. 333–338.

Kaza, S., Yao, L.C., Bhada-Tata, P., and Van Woerden, F., What a Waste 2.0 : A Global Snapshot of Solid Waste Management to 2050 2018. Retrieved from Washington, DC: http://hdl.handle.net/10986/30317

Kenya National Bureau of Statistics, 2019 Kenya population and housing census, Volume II: Distribution of population by administrative units. 2019.

Khan, S.M., Husain, T., Khan, H.U., 1987. Sanitary landfill alternatives in Saudi Arabia - A Case Study. Municipal Engineers 4, 227–237.

Kigozi, R., Aboyade, A., Muzenda, E., 2014b. Technology selection of biogas digesters for OFMSW via multi-criteria decision analysis. Lecture notes in engineering and computer science 2, 1069–1075.

Kigozi, R., Aboyade, A., Muzenda, E., 2014a. Sizing of an Anaerobic Biodigester for the Organic Fraction of Municipal Solid Waste. Proceedings of the World Congress on Engineering and Computer Science 2.

Kumar, S., Chiemchaisri, C., Mudhoo, A., 2011. Bioreactor landfill technology in municipal solid waste treatment: An overview. Crit. Rev. Biotechnol. 31 (1), 77–97. doi:10.3109/07388551.2010.492206.

Levis, J.W., Barlaz, M.A., 2011. What Is the Most Environmentally Beneficial Way to Treat Commercial Food Waste? Environ. Sci. Technol. 45 (17), 7438–7444. doi:10.1021/es103556m.

Li, H., Nitivattananon, V., Li, P., 2015. Municipal solid waste management health risk assessment from air emissions for China by applying life cycle analysis. Waste Manage. Res. 33 (5), 401–409. doi:10.1177/0734242x15580191.

Li, C., Wang, F., Zhang, D., Ye, X., 2016. Cost management for waste to energy systems using life cycle costing approach: A case study from China. J. Renewable Sustainable Energy 8 (2), 025901. doi:10.1063/1.4943092.

Lino, F.A.M., Ismail, K.A.R., 2013. Alternative treatments for the municipal solid waste and domestic sewage in Campinas, Brazil, Resources. Conservation and Recycling 81, 24–30. doi:10.1016/j.resconrec.2013.09.007.

Lino, F.A.M., Ismail, K.A.R., 2017. Incineration and recycling for MSW treatment: Case study of Campinas. Brazil, Sustainable Cities and Society 35, 752–757. doi:10.1016/j.scs.2017.09.028.

Lino, F.A.M., Ismail, K.A.R., 2018. Evaluation of the treatment of municipal solid waste as renewable energy resource in Campinas. Brazil, Sustainable Energy Technologies and Assessments 29, 19–25. doi:10.1016/j.seta.2018.06.011.

Luoranen, M., Horttanainen, M., 2007. Feasibility of energy recovery from municipal solid waste in an integrated municipal energy supply and waste management system. Waste Manage. Res. 25 (5), 426–439. doi:10.1177/0734242x07076943.

Méry, J., Bayer, S., 2005. Comparison of external costs between dry tomb and bioreactor landfills: taking intergenerational effects seriously. Waste Manage. Res. 23 (6), 514–526. doi:10.1177/0734242x05060857.

Madon, I., Drev, D., Likar, J., 2019. Long-term risk assessments comparing environmental performance of different types of sanitary landfills. Waste Manage. 96, 96–107. doi:10.1016/j.wasman.2019.07.001.

Maimone, M., 1985. An Application of Multi-Criteria Evaluation in Assessing Municipal Solid Waste Treatment and Disposal Systems. Waste Manage. Res. 3 (1), 217–231. doi:10.1177/0734242x8500300128.

Malakahmad, A., Abualqumboz, M.S., Kutty, S.R.M., Abunama, T.J., 2017. Assessment of carbon footprint emissions and environmental concerns of solid waste treatment and disposal techniques; case study of Malaysia. Waste Manage. 70, 282–292. doi:10.1016/j.wasman.2017.08.044.

Manfredi, S., Christensen, T.H., 2009. Environmental assessment of solid waste landfilling technologies by means of LCA-modeling. Waste Manage 29 (1), 32–43. doi:10.1016/j.wasman.2008.02.021.

Manyi-Loh, C.E., Mamphweli, S.N., Meyer, E.L., Okoh, A.I., 2019. Microbial anaerobic digestion: process dynamics and implications from the renewable energy, environmental and agronomy perspectives. Int. J. Environ. Sci. Technol. 16 (7), 3913–3934. doi:10.1007/s13762-019-02380-w.

Masebinu, S.O., Akinlabi, E.T., Muzenda, E., Aboyade, A.O., and Mbohwa, C., Experimental and feasibility assessment of biogas production by anaerobic digestion of fruit and vegetable waste from Joburg Market, Waste Manage. 75 (2018) 236–250. https://doi.org/10.1016/j.wasman.2018.02.011.

Mato, R.R.A.M., 1999. Environmental implications involving the establishment of sanitary landfills in five municipalities in Tanzania: the case of Tanga municipality. Resour. Conserv. Recycl. 25 (1), 1–16. doi:10.1016/S0921-3449(98)00038-X.

Mehta, Y.D., Shastri, Y., Joseph, B., 2018. Economic analysis and life cycle impact assessment of municipal solid waste (MSW) disposal: A case study of Mumbai. India, Waste Manage. Res. 36 (12), 1177–1189. doi:10.1177/0734242x18790354.

Menikpura, S.N.M., Gheewala, S.H., Bonnet, S., 2012. Sustainability assessment of municipal solid waste management in Sri Lanka: problems and prospects. J. Mater. Cycles Waste Manage. 14 (3), 181–192. doi:10.1007/s10163-012-0055-z.

Menikpura, S.N.M., Sang-Arun, J., Bengtsson, M., 2013. Climate co-benefits of energy recovery from landfill gas in developing Asian cities: a case study in Bangkok. Waste Manage. Res. 31 (10), 1002–1011. doi:10.1177/0734242x13492004.

Munala, G., Moirongo, B.O., 2011. The need for an integrated solid waste management in Kisumu, Kenya. Journal of Agriculture, Science and Technology 13 (1). http://journals.jkuat.ac.ke/index.php/jagst/article/view/138.

Murphy, J.D., McKeogh, E., 2004. Technical, economic and environmental analysis of energy production from municipal solid waste. Renewable Energy 29 (7), 1043–1057. doi:10.1016/j.renene.2003.12.002.

Mustafa, S.S., Mustafa, S.S., Mutlag, A.H., 2013. Kirkuk municipal waste to electrical energy. Int. J. Electr. Power Energy Syst. 44 (1), 506–513. doi:10.1016/j.ijepes.2012.07.053.

National Environment Management Authority, The National Solid Waste Management Strategy. Kenya, 2014.

Ngusale, G.K., Oloko, M., Agong, S., Nyakinya, B., 2017. Energy recovery from municipal solid waste, Energy Sources, Part A: Recovery. Utilization, and Environmental Effects 39 (16), 1807–1814. doi:10.1080/15567036.2017.1376007.

Ogunjuyigbe, A.S.O., Ayodele, T.R., Alao, M.A., 2017. Electricity generation from municipal solid waste in some selected cities of Nigeria: An assessment of feasibility, potential and technologies. Renewable Sustainable Energy Rev. 80, 149–162. doi:10.1016/j.rser.2017.05.177.

Olugasa, T.T., Odesola, I.F., Oyewola, M.O., 2014. Energy production from biogas: A conceptual review for use in Nigeria. Renewable Sustainable Energy Rev. 32, 770–776. doi:10.1016/j.rser.2013.12.013.

Pacey, J., Augenstein, D., Morck, R., Reinhart, D., Yazdani, R., 1999. The Bioreactor Landfill - An innovation in Solid Waste Management. MSW management, pp. 53–60.

Peerapong, P., Limmeechokchai, B., 2016. Waste to Electricity Generation in Thailand: Technology, Policy, Generation Cost, and Incentives of Investment. Eng. J. 20 (4), 171–177. doi:10.4186/ej.2016.20.4.171.

Rezaei, M., Ghobadian, B., Samadi, S.H., Karimi, S., 2018. Electric power generation from municipal solid waste: A techno-economical assessment under different scenarios in Iran. Energy 152, 46–56. doi:10.1016/j.energy.2017.10.109.

Roopnarain, A., Adeleke, R., 2017. Current status, hurdles and future prospects of biogas digestion technology in Africa. Renewable Sustainable Energy Rev. 67, 1162–1179. doi:10.1016/j.rser.2016.09.087.

Rupf, G.V., Bahri, P.A., de Boer, K., McHenry, M.P., 2017. Development of an optimal biogas system design model for Sub-Saharan Africa with case studies from Kenya and Cameroon. Renewable Energy 109, 586–601. doi:10.1016/j.renene.2017.03.048.

Salleh, N.F.D.M., Hamid, K.H.K., 2013. Leachate Characterization from a Closed Landfill in Air Hitam, Puchong, Malaysia. Malaysian Journal of Analytical Sciences 17 (1), 24–29. http://inis.iaea.org/search/search.aspx?orig_q=RN. 44127743.

Salvador, R., Barros, M.V., Rosário, J.G.D.P.D., Piekarski, C.M., da Luz, L.M., de Francisco, A.C., 2019. Life cycle assessment of electricity from biogas: A systematic literature review. Environ. Prog. Sustainable Energy 38 (4), 13133. doi:10.1002/ep.13133.

Sibanda, G., Musademba, D., Chihobo, H.C., and Zanamwe, L., A Feasibility Study of Biogas Technology to Solving Peri-urban Sanitation Problems in Developing Countries. A Case for Harare, Zimbabwe, 2013 2(2) (2013) 8. 10.14710/ijred.2.2.97-104.

Sibanda, L.K., Obange, N., Awuor, F.O., 2017. In: Challenges of Solid Waste Management in Kisumu, 28. Urban Forum, Kenya, pp. 387–402. doi:10.1007/s12132-017-9316-1.

Sivakumar Babu, G.L., Lakshmikanthan, P., Santhosh, L.G., 2014. Life Cycle Analysis of Municipal Solid Waste (MSW) Land Disposal Options in Bangalore City. In: International Conference on Sustainable Infrastructure, pp. 795–806.

Sudibyo, H., Majid, A.I., Pradana, Y.S., Budhijanto, W., Deendarlianto, Budiman, A., 2017. Technological Evaluation of Municipal Solid Waste Management System in Indonesia. In: Energy Procedia, 105, pp. 263–269. doi:10.1016/j.egypro.2017.03.312.

Thanh, N.P., Matsui, Y., 2012. An evaluation of alternative household solid waste treatment practices using life cycle inventory assessment mode. Environ. Monit. Assess. 184 (6), 3515–3527. doi:10.1007/s10661-011-2205-5.

Thanh, N.P., Matsui, Y., 2013. Assessment of potential impacts of municipal solid waste treatment alternatives by using life cycle approach: a case study in Vietnam. Environ. Monit. Assess. 185 (10), 7993–8004. doi:10.1007/s10661-013-3149-8.

The Sunday Standard, Governor Anyang' Nyong'o gets down to work amid high expectations. https://www.standardmedia.co.ke/politics/article/2001252238/what-governor-anyang-nyongo-wants-to-achieve-in-100-days, 2017. (Accessed 13 June 2021)

Tolis, A., Rentizelas, A., Aravossis, K., Tatsiopoulos, I.Karagiannidis, A. (Ed.), 2012. Decisions Under Uncertainty in Municipal Solid Waste Cogeneration Investments. Waste to Energy: Opportunities and Challenges for Developing and Transition Economies 197–218.

UNEP and ISWA, Global Waste Management Outlook 2015. Retrieved from http://hdl.handle.net/20.500.11822/9672

UNEP, Africa Waste Management Outlook - Summary for Decision-Makers 2018. Retrieved from http://hdl.handle.net/20.500.11822/25515

UNFCCC, The Community Cooker - Kenya. https://unfccc.int/climate-action/momentum-for-change/activity-database/the-community-cooker, 2021. (Accessed 23 May 2021)

Warith, M., Li, X., Jin, H., 2005. Bioreactor landfills: State-of-the-Art-Review. Emirates Journal for Engineering Research 10, 1–14.

World Bank, Decision Makers' Guide to Municipal Solid Waste Incineration 1999. Retrieved from Washington, D.C

Xin-gang, Z., Gui-wu, J., Ang, L., Yun, L., 2016. Technology, cost, a performance of waste-to-energy incineration industry in China. Renewable Sustainable Energy Rev. 55, 115–130. doi:10.1016/j.rser.2015.10.137.

Yong, Z.J., Bashir, M.J.K., Ng, C.A., Sethupathi, S., Lim, J.W., Show, P.L., 2019. Sustainable Waste-to-Energy Development in Malaysia: Appraisal of Environmental, Financial, and Public Issues Related with Energy Recovery from Municipal Solid Waste. Processes 7 (10), 676. https://www.mdpi.com/2227-9717/7/10/676.

Zhang, H., Zhang, D.-Q., Jin, T.-F., He, P.-J., Shao, Z.-H., Shao, L.-M., 2011. Environmental and economic assessment of combined biostabilization and landfill for municipal solid waste. J. Environ. Manage. 92 (10), 2533–2538. doi:10.1016/j.jenvman.2011.05.018.