Technical and Economic Evaluation of Organic Waste Management Method in the Western Province: A Comparative Analysis of Anaerobic Digestion, Sanitary Landfill, and Composting

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1. Introduction

Proper waste management is a solution for achieving sustainable development, especially in regions like Sri Lanka experiencing population growth and urbanization and straining waste management systems. To address these challenges, an integrated approach to managing waste has emerged as a solution. This study compares three waste management methods – Anaerobic Digestion (AD), Sanitary Landfill (SL), and Composting – to determine their effectiveness, sustainability, and contribution to the environment in Sri Lanka. Anaerobic digestion is a method of treating waste known for converting waste into valuable resources like biogas and nutrient-rich digestate (Lamolinara et al., 2022). Its role in reducing emissions and generating energy aligns with the objective of sustainable waste management. On the other hand, Sanitary Landfill, a necessary disposal technique, requires careful consideration in design and operation (Ozbay et al., 2021). A designed Sanitary Landfill helps minimize impacts by effectively managing organic waste while mitigating issues such as groundwater contamination and greenhouse gas emissions. Additionally, composting is a process that transforms waste into nutrient-rich soil conditioners. It promises to improve soil health and reduce reliance on chemical fertilizers (Oyege & Balaji Bhaskar, 2023). Important social factors in the context of waste management, are community acceptance and participation which play a determinate role in the success or failure of systems designed to deal with the problem (Afshar et al., 2020). Involving the local community in the planning and decision-making processes can make waste management practices more efficient, effective, and compliant. This research examines waste management techniques considering factors such as efficiency, environmental impact, cost-effectiveness, and suitability within Sri Lanka's socio-economic context. By comparing Anaerobic Digestion Sanitary Landfill and Composting approaches, our study intends to provide insights for policymakers and stakeholders in Sri Lanka seeking waste management strategies for long-term sustainability.

1.1 Mechanical Biological Treatment (MBT)

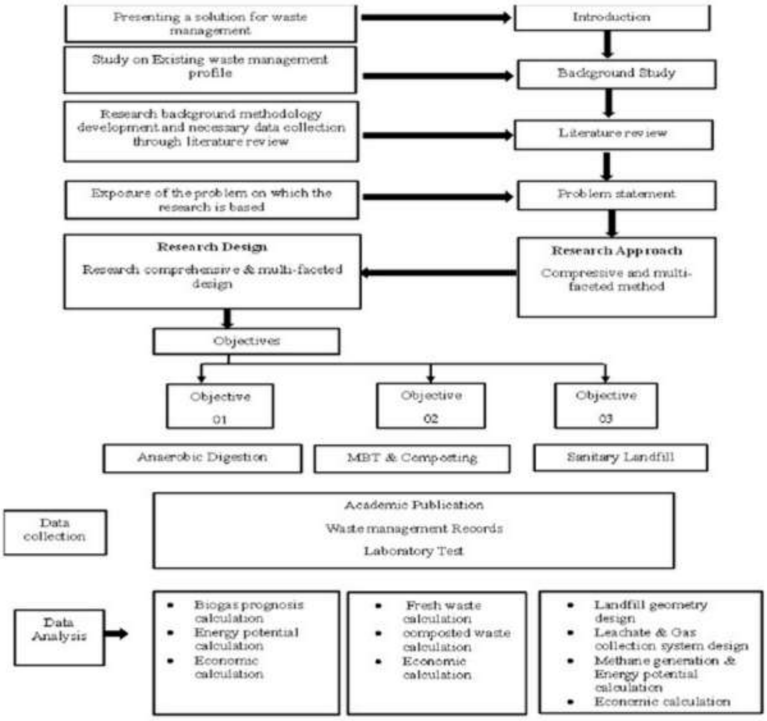

Fig. 1. Conceptual Framework

Mechanical Biological Treatment (MBT) is a waste management strategy combining mechanical and biological processes to efficiently treat municipal solid waste (MSW). Many studies have explored MBT's applications, advantages, and challenges, highlighting its role in waste treatment. MBT involves a series of stages to manage waste effectively. It begins with treatment, which includes shredding, sieving, and magnetic separation. This approach significantly reduces the volume of waste that goes to landfills while improving resource recovery, as demonstrated by Gundupalli et al., (2017) and (Bernat, 2023) who emphasize how it enhances waste processing optimization.

1.2 Objectives

The main objective of this research study is to conduct a comprehensive comparative analysis of anaerobic digestion, sanitary landfill, and composting as integrated approaches to organic waste management in Sri Lanka, focusing on their sustainability implications. To achieve this, the following sub-objectives were investigated: the feasibility and efficiency of anaerobic digestion and sanitary landfilling in generating biogas from organic waste streams prevalent in Western Province, Sri Lanka, and the feasibility and efficiency of compost production from Western provinces.

2. Methodology

2.1 Experiment Method

The research team in Sri Lanka collected data through secondary methods, field visits, interviews, and on-site observations at waste management facilities and composting sites. They also gathered information from reputable sources like government reports and waste management records. The study analyzed carbon content in waste samples from anaerobic digestion and sanitary landfill sites, using titration techniques and moisture content tests. Degradable Organic Carbon (DOC) was determined using a modified Walkley-Black chromic acid wet oxidation method, providing insights into the biodegradability of organic matter and aiding in waste management strategies and resource recovery potential.

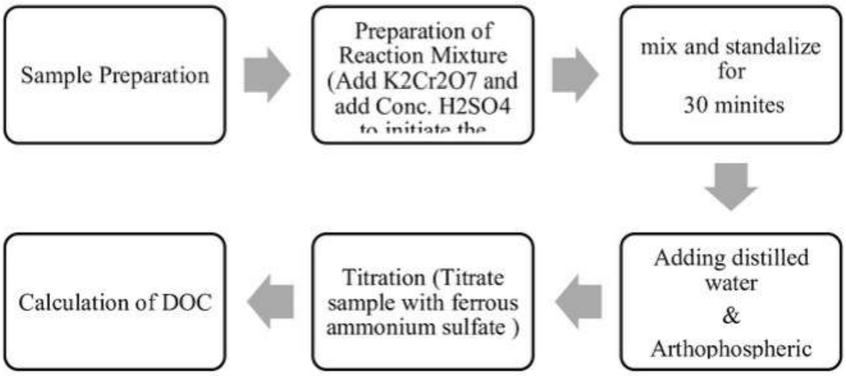

Fig. 2. DOC Test

2.2 Data Analysis

All the data analysis techniques were based on the IPCC-CDM tool.

2.2.1 Anaerobic Digestion

Reactors

Here floating drum reactor was used for anaerobic digestion which contains a volume of 2500m^3.

$$Necessary\ reactor\ volume = (optimal\ water\ volume + DM\ Input) \times DF \qquad (1)$$

Number of reactors

$$Number\ of\ reactos = \frac{Necessary\ reactor\ volume}{Maximum\ reactor\ size} \qquad (2)$$

Source: (IPCC CDM Tool, 2015)

Biogas generation

Biogas volume estimation.

$$CH4\ in\ biogas = Amount\ of\ Cin\ biogas \times 0.6 \tag{3}$$

$$CO2\ in\ biogas = Amount\ of\ Cin\ biogas\ \times 0.4 \tag{4}$$

$$Total\ Biogas = CH4\ in\ biogas + CO2in\ biogas \tag{5}$$

Source: (IPCC CDM Tool, 2015)

Electricity generation potential

This involves estimating how much electricity can be produced from the biogas generated through digestion. Additionally, the study will determine how many households can benefit from this generated power.

Calculating Electrical Generation Capacity: Source: (IPCC CDM Tool, 2015)

$$Electricity\ generation = EC \times EEOM(Combustion\ unit) \tag{6}$$

Converting Biogas to Electricity: Source: (IPCC CDM Tool, 2015)

$$Power\ supply\ for\ homes = \frac{Electricity\ generation \times 1000}{Electric\ power\ consumption\ per\ home} \tag{7}$$

Analyzing Economics Revenue Estimation: Source: (IPCC CDM Tool, 2015)

$$Feed\ in\ revenues = \frac{Electricity\ generation \times 1000 \times Feed - in\ tariff}{100} \tag{8}$$

MBT and Composting

Compost Volume Calculation: Source: (IPCC CDM Tool, 2015)

$$Composted\ Volume\ Per\ Day = \frac{\frac{Waste\ for\ composting\ area}{Density\ of\ Uncompacted\ Wate(\rho_c)}}{365} \tag{9}$$

Required Volume for Composting Period

$$Required\ volume = Compost\ volume\ per\ day \times 7 \times Duration\ of\ composting \tag{10}$$

Number of Compost Rows for Composted Material

$$Numb\ of\ compost\ rows\ of\ fresh\ material = \frac{V_{CR}}{Volume\ of\ one\ compost\ row} \tag{11}$$

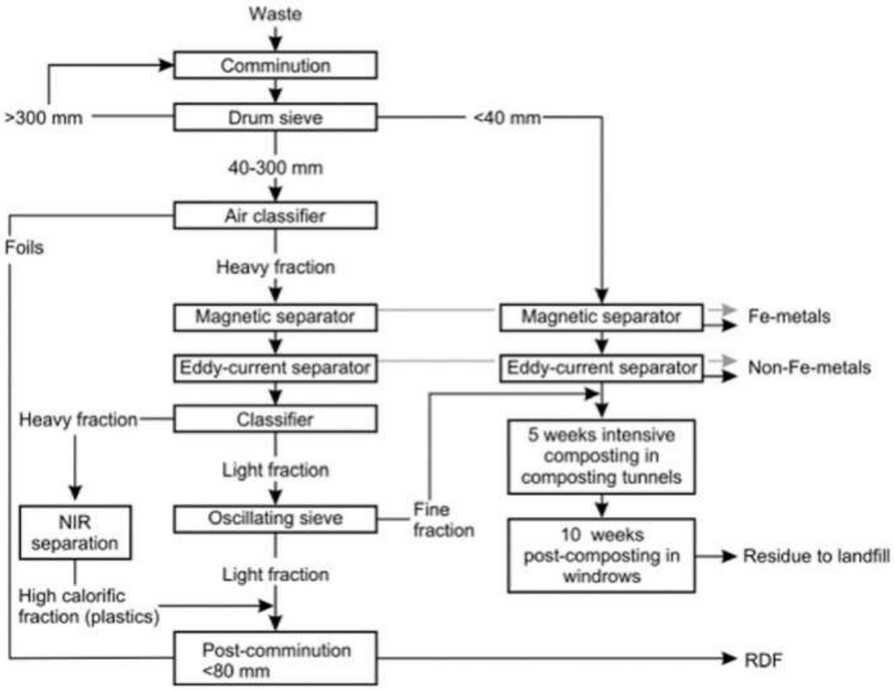

Fig. 3. Mechanical biological pretreatment (THOMAS H. CHRISTENSEN, 2010)

2.3 Sanitary Land Filling

Landfill Geometry and Parameters

The shape and structure of a landfill that includes factors like the angle of the landfill's sides, the materials lining the base, and the cover system. (IPCC CDM Tool, 2015)

1 - An appropriate landfill geometry

The landfill body will be approximated as a straight truncated pyramid with a rectangular base G_2 (see figure). Its volume is given by $V_{calc} = \frac{h}{3} \cdot \left(G_1 + G_2 + \sqrt{G_1 \cdot G_2}\right)$,

where $G_1 = l_1 \cdot w_1;\ G_2 = l_2 \cdot w_2;\ l_2 = l_1 + 2 \cdot h \cdot slope;\ w_2 = w_1 + 2 \cdot h \cdot slope.$

Source: (IPCC CDM Tool, 2015)

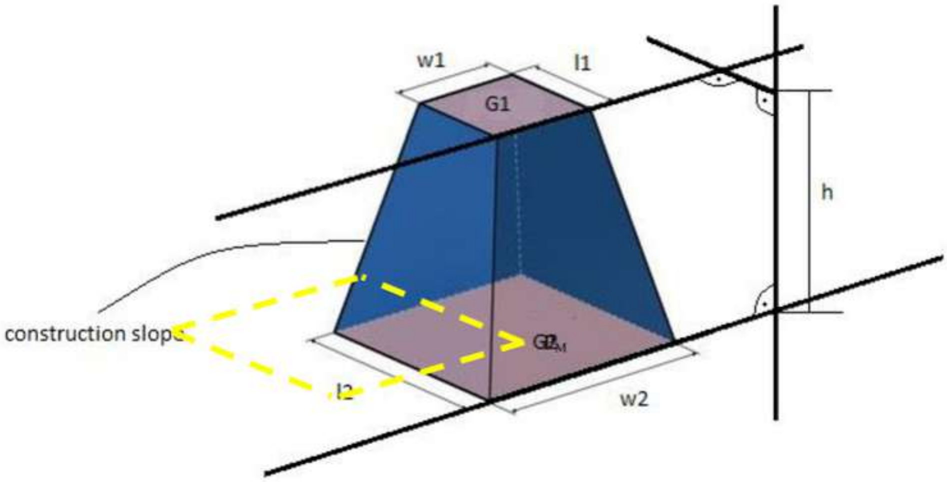

Fig. 4. Geometry of Landfill Site

Leachate collection system: Source: (IPCC CDM Tool, 2015)

Determine the Area per Drainage Cell (A_C). That helps to determine each drainage cell's size, ensuring efficient leachate collection.

$$A_c = \frac{P_D \times P_C}{2} \tag{12}$$

$$Pipe\ length\ per\ drainage\ cell\ (P_{DC}) = \frac{Pc}{2} + \frac{P_D}{2} \tag{13}$$

$$Number\ of\ drainage\ cells\ nAC = \frac{G2}{A_C} \tag{14}$$

Following that calculate the Number of Collection Pipes and Drainage Pipes. These numbers are essential for designing and installing a functioning leachate collection network. Source: (IPCC CDM Tool, 2015)

$$Number\ of\ collection\ pipes = \frac{W_2}{P_C} \tag{15}$$

$$Number\ of\ drainage\ pipes = \frac{nAC}{2} \tag{16}$$

Lastly, determine the Length of Both Collection and Drainage Pipes (L_T). This comprehensive measurement considers all pipes required for a leachate collection system.

$$L_T = P_{DC} + n_{AC} + P_M + P_{LTP} \tag{17}$$

Gas collection system: Source: (IPCC CDM Tool, 2015)

$$Total\ number\ of\ gas\ wells = \frac{G2}{D_{GW} \times D_{GW}} \tag{18}$$

In addition, calculate the number of collection stations. These stations serve as centralized points where the collected gas is processed and prepared for use or safe disposal.

$$Number\ of\ collection\ stations = \frac{Total\ number\ of\ gas\ wells}{12 + 1} \tag{19}$$

Source: (IPCC CDM Tool, 2015)

By conducting these calculations, a gas collection system was designed.

Methane Generation Potential

Researchers used the Clean Development Mechanism Project Design Document (CDM PDD) equation to estimate biogas emission during the landfill phase (IPCC CDM Tool, 2015). This equation considers waste type, biogas generation rate, decay rate, and methane capture efficiency.

$$\{Biomethane\ Generation\} = \varphi \times \left(1 - f_y\right) \times GWP_{CH4} \times (1 - XO) \times \frac{16}{12} \times F \times DOC_{f,y} \times MCF_y \times \sum_{i=1}^{y} \sum_j \left(W_{j,i} \times DOC_j \times e^{-kj \times (y-x)} \times (1 - e^{-kj})\right) \tag{20}$$

Source: (IPCC CDM Tool, 2015)

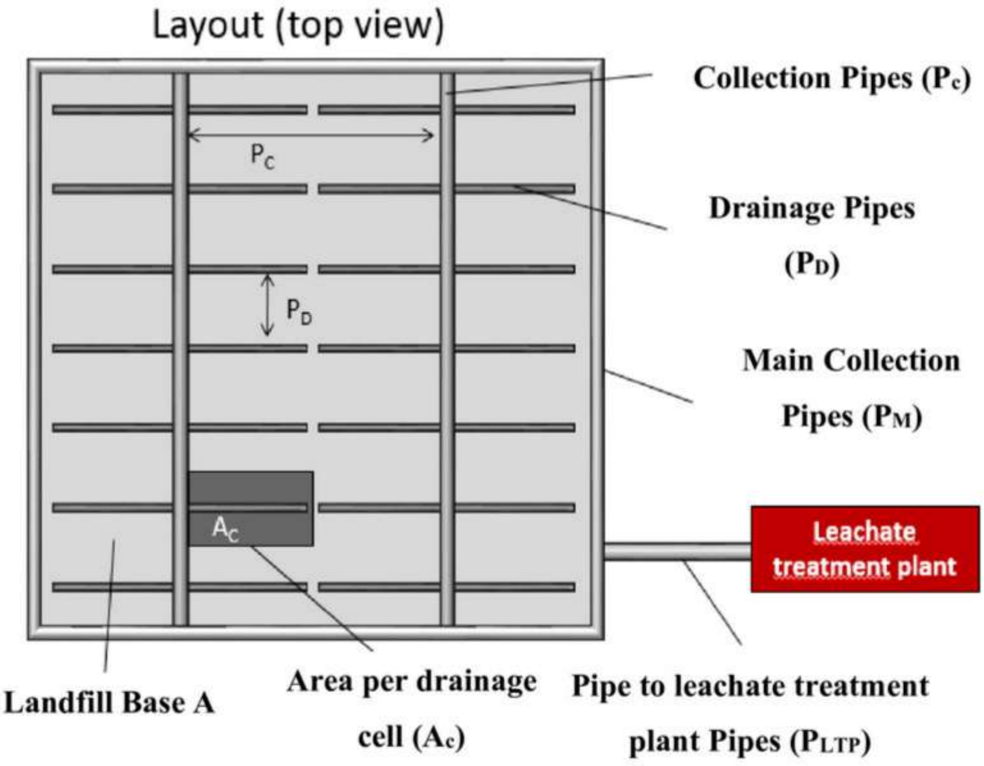

Figure 5: Leachate collection system

3. Results and Discussion

3.1 Anaerobic Digestion

Table 1. Compositions of carbon and gases

Parameters	Values
Amount of potentially degradable C in biowaste input	256,814 t/a
Remaining degradable C in digestate	128,407 t/a
Amount C in biogas	128,407 t/a
Biomethane potential rate	6,414,470 kmol/a
CO_2 in biogas	4,276,313 kmol/a
Total biogas	239,612,529 m^3/a

The JICA Report 2023 shows that Sri Lanka's western province generates 642,035 tons of organic waste annually, with potential for biogas production through anaerobic digestion. Around 40-50% range of organic carbon has the potential to convert into biogas (Dinh et al., 2019), and this calculated values in table 2-1 is based on the 50% from degradable C was converted into biogas. The process yields methane and carbon dioxide, with a total biogas production of 239,612,529m3/a, indicating significant potential for waste reduction.

Table 2. Power and Electricity Generation Capacities

Parameters	**Values**
Electrical capacity (total heating value)	5,158,809,836MJ/a
Electricity generation	429,907MWh/a
Power supply for homes	184,112homes
Power supply for X persons	681,301pers

To convert this biogas into electricity, consider the amount of methane generated and its heating value (36MJ/m^3) (The Engineering ToolBox, 2023). Regarding energy analysis, the total heating value equals 5,158,809,836 MJ/a. That leads to an estimated electricity generation capacity of 429,901MWh/a or 49.1MW. These figures demonstrate a potential for producing electricity from biogas. Comparing this energy output to the electricity consumption patterns in Sri Lanka's Western Province reveals that the biogas could power around 184,112 households or serve 681,301 persons. From a standpoint, the revenue generated from feeding electricity into the grid using biogas is LKR 9,887,718,852.62 per year, highlighting digestion's potential as a waste-to-energy solution in Sri Lanka. Considering the calculated rates of biogas generation and energy output, it is determined that an optimal reactor volume of 140,720m^3 would be required for biogas production. That would necessitate a total of 56 reactors with a size of 2500m^3 (Ministry of New and Renewable Energy India, 2023).

3.2 Composting Site

The Mechanical Biological Treatment (MBT) approach to waste management involves a composting process that processes 2932m^3 of waste volume daily, requiring 342 compost rows to accommodate 15 weeks period. The average daily accumulate waste volume was calculated based on the total waste weight accumulate per year of 642,035t/a, this value is calculated on considering forecasted waste accumulation from 2025 to 2042 period (JICA, 2023). The process produces 1368m of compost, resulting in 143,652m over 15 weeks, requiring around 160 rows. On average, 251 compost rows are needed to handle both composted materials. The site size required for this process is 25.0820 hectares, requiring a significant land area for implementation. The assumptions were made for this calculation, such as uncompacted fresh waste density as 0.6 tone/m^3, compacted waste density 0.9 tone/m^3, waste density after MBT process 1.1 tone/m^3, mass loss through composting (water and organic matter) as 30 %, and 15-week composting period.

Table 3. Compost production results

Parameters	Values
Fresh waste volume per day	2932m^3/day
Required volume for composting period (15 weeks)	307,825m^3
Number of compost rows from fresh material	342rows
Compost volume per day	1368m^3/day
Required volume for composting period	143,652m^3
Number of compost rows of composted material	160 rows
Average	251 rows
Site size	25.0820ha

3.3 Sanitary Landfill Design and Biogas Production

The calculations for methane generation during 2025-2042 reveal an opportunity to produce biogas from organic waste. In 2042, these combined waste streams generated a peak of 49,328 tons of methane. That indicates a potential for harnessing biogas to generate energy and promote sustainability.

Table 4. CH_4 generation over the operation period

Year	amount landfilled [$t_{\text{wet waste}}$]	Food Waste		Garden and Park Waste		Wood Waste		Paper		Textiles	
	t	t	tCH4	t	tCH4	t	tCH4	t	tCH4	t	tch4
2025	395,660	178047	7395	17805	125	7913	26	35214	214	13848	51
2026	418,290	188231	12776	18823	238	8366	53	37228	426	14640	101
2027	440,555	198250	16799	19825	340	8811	81	39209	636	15419	150
2028	462,090	207941	19898	20794	433	9242	109	41126	843	16173	199
2029	487,275	219274	22446	21927	520	9746	137	43367	1050	17055	248
2030	511,730	230279	24612	23028	601	10235	167	45544	1256	17911	296

2031	539,835	242926	26589	24293	678	10797	197	48045	1464	18894	345
2032	566,625	254981	28415	25498	751	11333	228	50430	1672	19832	394
2033	581,810	261815	29922	26181	818	11636	259	51781	1874	20363	442
2034	606,630	272984	31397	27298	882	12133	290	53990	2075	21232	490
2035	626,705	282017	32761	28202	942	12534	322	55777	2275	21935	537
2036	650,430	292694	34119	29269	1001	13009	354	57888	2473	22765	584
2037	677,440	304848	35534	30485	1059	13549	387	60292	2673	23710	631
2038	702,990	316346	36960	31635	1116	14060	421	62566	2873	24605	678
2039	728,905	328007	38400	32801	1172	14578	455	64873	3073	25512	725
2040	752,995	338848	39816	33885	1227	15060	489	67017	3273	26355	772
2041	782,195	351988	41311	35199	1283	15644	524	69615	3475	27377	820
2042	812,490	365621	42879	36562	1340	16250	560	72312	3680	28437	868
Sum [t]	10,744,650	4,835,093	522,027	483,509	14,526	214,893	5,059	956,274	35,305	376,063	8,330

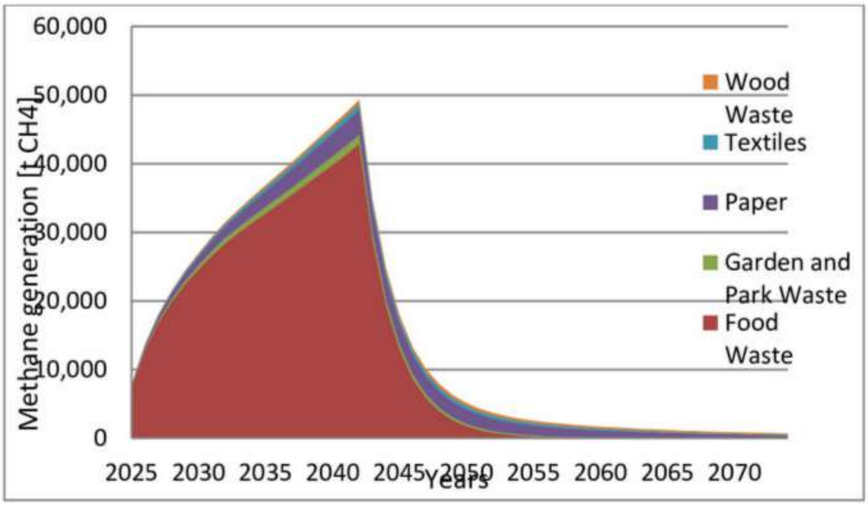

Fig. 6. Estimated CH_4 Generation 2025 – 2070

Economic analysis of landfill site

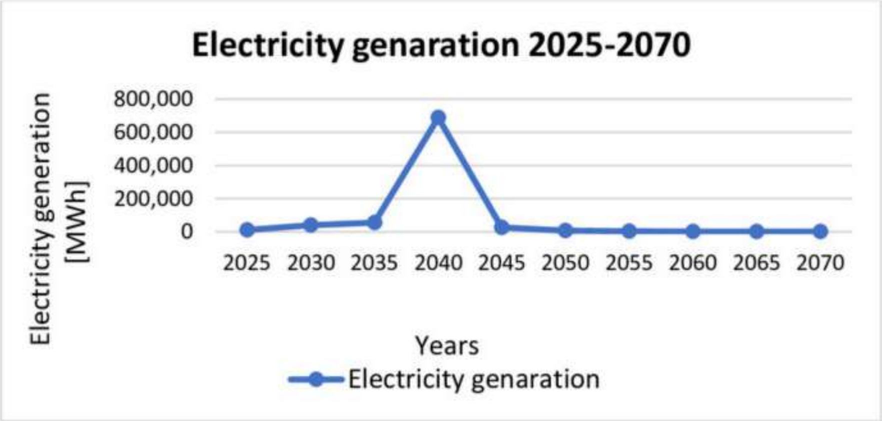

Fig. 7. Estimated electricity generation 2025 -2070

Design of Landfill Site

(a) Landfill Site Geometry

Table 5. Landfill site parameters

Parameters	**Values**
length without slope l1	1218m
width without slope w1	300m
length with slope l2	1368m
width with slope w2	450m
G1	3654400m^2
G2	615600m^2
Perimeter of the landfill PM	3636m

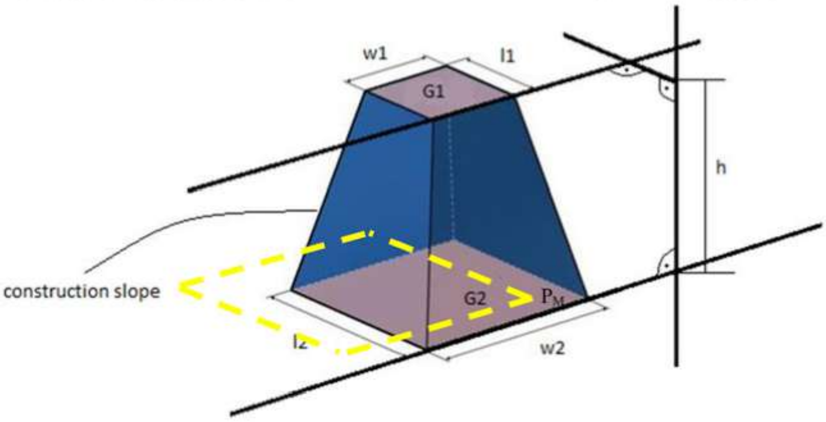

Fig. 8. Proposed landfill design

(b) Leachate Collecting System

Each drainage cell covers an area of 1,875m^2. A pipe length per drainage cell (P_{DC}) is 88m. The design requires a total of 164 drainage pipes and 3 collection pipes, which are distributed across 328 drainage cells. The combined collection and drainage pipes (L_T) length is 32,464m. This comprehensive network is efficient for managing leachate from the landfill.

(c) Gas Collection System

The design considers parameters such as the distance between gas wells and the total number required for the gas collection system. There is a distance of 65m between gas wells. Installing 146 gas wells with a maximum of 12 per collection station is recommended to ensure coverage for collecting landfill gas.

Table 6. Geometry and parameters for construct 3, 6, and 9 sanitary landfill sites

Parameters	**Values**			
		For 3 Sites	For 6 Sites	For 9 Sites
Waste volume	12,127,328m^3	4,042,443m^3	2,021,221m^3	347,481m^3
Landfill Geometry				
length without slope l1	1218m	351m	137m	67m
width without slope w1	300m	300m	300m	300m
length with slope l2	1368m	501m	287m	217m
width with slope w2	450m	450m	450m	450m
G1	3654400m^2	105371m^2	40953m^2	20010m^2
G2	615600m^2	225556m^2	128930m^2	97515m^2
Perimeter of the landfill PM	3636m	1902m	1473m	1333m
Leachate Collection System				
Area per drainage cell A_C	1875m^2	1875m^2	1875m^2	1875m^2
Pipe length per drainage cell P_{DC}	88m	88m	88m	88m
Number of drainage cells n_{AC}	328	120	69	52

Number of collection pipes	3	3	3	3
Number of drainage pipes	164	60	34	26
Total length of collection and drainage pipes L_T	32,464m	12,528m	7590m	5984m
Gas Collection System				
Total number of gas wells	146	53	31	23
# of collection stations	13	5	4	3

3.4 Overall Results Comparison

Table 7. Result Comparison

Parameters	Anaerobic Digestion	MBT& Composting	Sanitary Landfilling
Average Waste quantity / year	642,035 tones	642,035 tones	632,038 tones
Mass of compost /year		449,425t/a	
Electricity /year	429,901 MWh		65,850 MWh
Revenue / year	LKR 9,887,718,852	LKR 4,494,245,000	LKR 1,514,544,113

The total revenue tons of waste management are compared among waste management techniques. Significant revenue from Anaerobic Digestion LKR is 9,887,718,852.62 from producing electricity, which also yielded substantial revenue, with composting generating LKR 4,494,245,000.00. Sanitary landfilling contributing LKR 25,747,249,923.35.

4. Conclusion

The study delved into the intricacies of waste management within the Western Province, yielding several significant numerical findings. First and foremost, the total waste weight analyzed amounted to a substantial figure (642,035t/a), indicating the region's considerable waste generation rate. Anaerobic digestion emerged as a standout solution, demonstrating promising results with a noteworthy gas capacity and nutrient-rich compost produced from organic waste. The study identified a need for a considerable land area for adequate waste treatment facilities (25ha). Over the estimated 17-year period, anaerobic digestion contributed significantly to renewable energy production, generating a notable amount of electricity (429,901MWh). The implementation of waste-to-energy solutions also yielded substantial revenue, with composting generating LKR 4,494,245,000.00 and sanitary landfilling contributing LKR 25,747,249,923.35, further underscoring the economic viability of sustainable waste management practices. In conclusion, the study advocates for a holistic approach to waste management, emphasizing the importance of optimizing resource recovery, minimizing environmental impact, and advancing towards a circular economy model.

Keywords: Anaerobic Digestion, Biodegradable Waste, Composting, Sanitary Landfilling, Waste Management

Abbreviations

DF = Duration of fermentation
EC = Electrical capacity (total heating value)
EEOM = Electrical efficiency of motor (Combustion unit)
V_{CR} = Required volume for composting period
A_C = Area per drainage cell
P_D = Distance between drainage pipes
P_C = Distance between collection pipes
Next, calculate the Pipe Length per Drainage Cell (P_{DC}). This measurement is crucial in determining the length of pipes needed to collect and transport leachate effectively within each drainage cell.
n_{AC} = Number of Drainage Cells
A_C = Area per drainage cell
W_2 =width with slope
P_C = Distance between collection pipes
L_T - Total length of collection and drainage pipes
P_{DC} - Pipe length per drainage cell
n_{AC} - Number of drainage cells
P_M = Perimeter of the landfill
P_{LTP} = Distance to waste water treatment plant
D_{GW} = Distance between gas wells

Clean Development Mechanism Project Design Document (CDM PDD) equation
<u>Yearly model:</u>
X = Years in the time period
Y = Year (y is a consecutive period of 12 months)
$DOCf$,y= degradable organic carbon (DOC)
Wj, = Amount of solid waste type j disposed or prevented from disposal in the SWDS in the year x (t)

φy = Model correction factor

fy = Fraction of methane captured
$GWPCH4$ = Global Warming Potential of methane
OX = Oxidation factor (reflecting the amount of methane)
F = Fraction of methane in the SWDS gas (volume fraction)
$MCFy$ = Methane correction factor for year y
$DOCj$ = Fraction of degradable organic carbon in the waste type
k = Decay rate
j = residual waste or types of waste in the MSW

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