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# A study on small-scale municipal solid waste management practices and its impact on carbon emission and mitigation cost

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**Abstract**

Municipal solid waste management (MSWM) is arguably one of the most vital and challenging municipal services offered by the city councils around the world. Proper and efficient management of municipal solid waste (MSW) is vital for achieving sustainable development as the dilemmas associated with energy management, greenhouse gas (GHG) emission, waste-to-energy (WTE) cycle, climate change and economy are addressed. Ineffective waste management technique leads to adverse impacts on the environment, public health and lifestyle of future generations. Motivating governmental organizations across the world to take proactive measures to mitigate waste management techniques with less environmental impact and high financial return. A comparison study of five different MSWM techniques based on cost-benefit analysis and mitigation cost breakdown is presented in this paper to identify the most effective and efficient small-scale MSWM systems. The mitigation analysis utilizes the data obtained from the literature to calculate the greenhouse gas reductions, current net and the carbon mitigation cost of each method considering basic landfill technique as the baseline reference. Hybrid techniques like mechanical biological treatment (MBT) in combination with WTE outperforms the other techniques with lowest carbon mitigation cost ($27.3/metric tons of carbon dioxide equivalent (MTCO2e) without carbon emanation rate (CER) and $43.4/ MTCO2e with CER) and reduced GHG emission. Whereas the conventional WTE is ranked second with mitigation costs of $26.5/ MTCO2e without CER and $42.5/ MTCO2e with CER but this technique also offers the largest reductions in terms of greenhouse gases (1.06 million tons/tons of municipal solid waste) which make it stand out from others. Based on the results obtained from the study the economic and environmental impact caused by the usage of WTE or the hybrid MBT in small-scale MSWM system is proven to be highly beneficial and the introduction of carbon credit schemes reduces the carbon mitigation cost of each technique to a greater extent.

*Keywords: Municipal solid waste management(MSWM), greenhouse gas (GHG) emission, mechanical biological treatment (MBT), waste-to-energy (WTE), carbon mitigation cost, mitigation cost analysis*

## 1. Introduction

Factors like rapidly increasing population, urbanization and industrialization directly influence the rise of total MSW generation. In general, MSW refers to all chunks of wastes that include organic, glass, metal, paper, cardboard, etc., from residential (homes, apartments), public (schools, hospitals) and industrial areas of the city. According to the study conducted by the world bank’s waste management thematic group [1], the current generation of MSW is about 70 million tons per year in South Asian countries. By 2025, this figure is expected to triple to an approximate number of 200 million tons per year. Management of MSW has become and will be a major challenge for local authorities considering these

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staggering number, novel and innovative solutions to address this issue is evolving with technological development. However, countries like Philippines, Malaysia, Thailand and Sir Lanka experience a lack of resources/revenue to equip expensive technologies for managing solid waste due to the low gross domestic product (GDP) and high density of population. Introduction of appropriate MSWM techniques would effectively address the issue of improper waste management schemes is essential. According to the report published by united nations environment programme (UNEP) [2], the composition of organic waste in MSW is greater in developing countries compared to developed countries indicating the need of effective waste management strategies in developing nations. Low calorific property of organic waste emphasis the need for waste separation technology, mechanical treatment and biological treatment plants [3]. Identification of the most suited MSWM technique depends on many economic and environmental factors. In this manuscript, evaluation of five different waste management techniques namely: sanitary landfills, sanitary landfills with collection and gas flaring, landfills with electricity generation, WTE and mechanical and biological treatment (MBT) in combination with WTE is carried out by undertaking cost-benefit analysis and mitigation cost breakdown which helps us identify the most suited/feasible solution for small-scale MSWM system.

## 2. Municipal Solid Waste Management

Many legislative policies were framed based on the financial sustainability and feasibility of several aspects of MSWM, like generation, collection, elimination, etc., [2]. In addition to the conventional solid waste management practices, waste management strategies that include energy recovery were more environmentally friendly and cost-effective. Collection and usage of landfill gas or flare in sanitary landfills for electricity production and waste to energy systems are few of the MSWM techniques that are transforming the ideology of waste management into a new realm. The energy produced by using these waste management techniques are supplied to the industrial or domestic use, reducing the impact of fossil fuels on the environment. Furthermore, recycling energy from landfills reduces greenhouse gas emissions from conventional energy generation techniques and consist of high economic impact. Considering all these factors, the need for finding an optimum solution which addresses the financial, environmental and adaptability concerns of SWM is highlighted.

The global increase in the amount of municipal solid waste generated annually is influenced by the factors associated with the growth in the economy, industrialization, population and standard of living [4]. Fig. 1. represents the region-wise split up on the per-capita value of region wise MSW generation from which we can infer that the OECD countries in which Australia is a part off have an appreciable share [1]. Australia and New Zealand, in particular, have high per capita of MSW generated annually emphasizing the need for a fully functional and effective MSWM system [1].

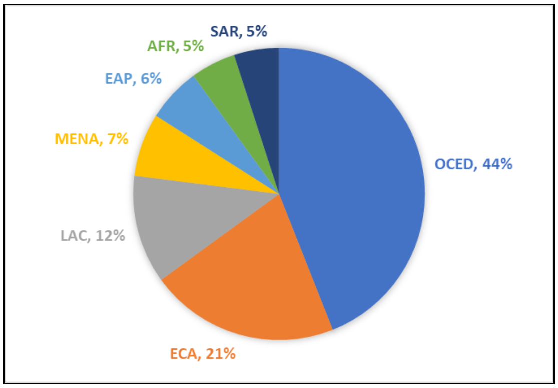


Fig. 1. Region wise per-capita of MSW generation (Kg/capita/day).

Understanding the composition of MSW is highly beneficial as it helps decision makers to plan a most suited MSWM approach for the specific region. Table 1. indicated the region-wise split up of the composition of the MSW and Fig. 2. denotes the composition of the OECD countries indicating that the need for an effective MSWM technique.

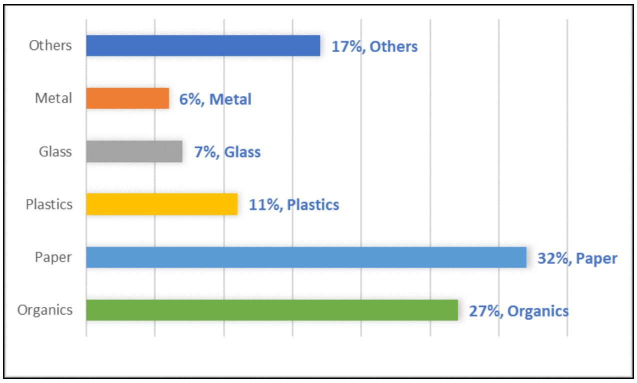


Fig. 2. The composition of MSW in OECD countries.

Lack of effective and sustainable waste management strategies leads to a wider scope of challenges that must be addressed, identification of such prominent parameters is obtained from the extensive review of literature undertaken in this study. The main challenges are categorized into three parts: institutional or financial challenges, technical challenges and education challenges [5]. Improper policies to promote SWM measures, lack proper funding, the absence of formal procedures and regulations are integrated into the category of institutional or financial challenges [6]. The effectiveness of MSWM system depends on the preference and interest of the governmental policies focused on addressing the management of excessive increase in municipal waste [7]. The efficient waste collection is considered as one prime part of waste management systems, based on the geographical location and availability of disposable landfills areas. The collected waste is recycled using methods like compositing considering the relationship to the time and regional characteristics [8]. Besides, the technical and financial challenges educating the inhabitants of the city to better understand the advantages of MSWM system considering its financial and environmental impact is essential [9].

Table 1. Region wise MSW composition

| Region | Organics | Paper | Plastics | Glass | Metal | Others |
|---|---|---|---|---|---|---|
| AFR | 57% | 9% | 13% | 4% | 4% | 13% |
| EAP | 62% | 10% | 13% | 3% | 2% | 10% |
| LCA | 47% | 14% | 8% | 7% | 5% | 19% |
| SAR | 50% | 4% | 7% | 1% | 1% | 37% |
| MENA | 61% | 14% | 7% | 4% | 4% | 10% |
| LAC | 54% | 16% | 12% | 4% | 2% | 12% |
| OECD | 27% | 32% | 11% | 7% | 6% | 17% |

Organization for Economic Co-operation and Development (OECD), Europe and Central Asia region (ECA), Latin America and the Caribbean region (LAC), Middle East and North Africa region(MENA), East Asia and Pacific region (EAP), Africa region (AFR), South Asia region (SAR)

## 3. Methodology

Following the order of waste management hierarchy [10], five common waste management techniques are considered for the mitigation study highlighted in the manuscript are explained in this section. The most basic waste management method is the sanitary landfilling without any energy recovery which is considered as the baseline reference and the other four techniques are used as the carbon mitigation options in the study. Data used in the cost-benefit analysis and carbon mitigation breakdown are obtained from inferences from previous studies from the literature. In the conventional landfilling technique, MSW is generally disposed of in a standard sanitary landfilling area which has impacts like polluting the soil and water resources, high GHG emission and wastage of huge areas occupied by wastage dumps. The second technique, expressed in the study involves flaring and gas collection of sanitary landfilling. In this method, the landfill gas will be collected and flared to reduce the direct GHG emissions. A more advanced sanitary landfilling technique which includes energy recovery is considered as the third technique. The landfill gas collected from the sanitary landfilling will be used to generate electricity. Direct GHG emissions can be further reduced and sales of electricity generated to act as an income to the system reducing the total operational cost. WTE is a technique which includes methodologies like moving grate combustion chamber, air pollution control system, etc., After combustion of MSW, the metal leftovers in the ash are recovered and recycled, whereas the rest ash goes to the sanitary landfilling. Finally, the hybrid technique which uses an MBT plant along with a WTE system is considered as the final mitigation option of the study. Mechanical treatment technologies in combination with biological technologies are used to recycle a certain amount of materials. The slag from this process will go to a WTE plant making it a prominent technique to be used which is also highlighted by the results obtained from the study.

### *3.1. Cost-benefit analysis*

The carbon mitigation cost of each technique expressed in this study is based on the cost of abatement measures taken to ensure reduced GHG emission, operating costs and increased potential benefit. The methodology used to calculate the overall cost of carbon mitigation is based on the principal idea proposed by Ibrahim and Kennedy [11] for constructing marginal abatement cost curves of climatic action. The cost of effectiveness of the mitigation measure is equal to the ratio of the net present cost and avoided GHG emissions as expressed in equation 1 below.

$$\text{(Dollars per MTCE reduction)} = \text{(Dollars per ton MSW)} / \text{(MTCE per ton MSW)} \tag{1}$$

The net present cost (NPC) is expressed as the difference between the mitigation measure and the baseline value, where the value of the mitigation measure is calculated by estimating the difference of the sum of the capital cost and the operating cost with the total revenue of the technique excluding the discount rate in equation 2. GHG emissions avoided (CE) is expressed as the difference of the CE value of the mitigation option and the baseline value.

$$\text{NPC (Dollars per ton MSW)} = \text{(Capital cost + Operating cost - Revenue) mitigation measure - baseline} \tag{2}$$

$$\text{CE (MTCE per ton MSW)} = \text{CE mitigation measure - CE baseline} \tag{3}$$

#### *3.1.1. Conventional sanitary landfilling: (baseline)*

The actual amount of equivalent carbon dioxide emitted per ton of MSW landfilled is calculated based on the assumptions obtained from previous studies of Themelis et al. [12]. The average composition of combustible materials in MSW can be expressed as $C_6H_{10}O_4$ (kmol wt=146kg). The anaerobic digestion of MSW materials is expressed as a chemical reaction highlighted in equation 4.

$$C_6H_{10}O_4 + 1.5\ H_2O = 3.25\ CH_4 + 2.75\ CO_2 \tag{4}$$

Landfill gas is a by-product of the biodegradation of the waste in landfills, it generally contains methane ($CH_4$), carbon dioxide ($CO_2$), and little portions of non-methane natural aggravates that contains incorporate air contaminations and unstable natural mixes. If it is assumed that only 50% of the total landfilled biomass of MSW emits methane, the generation of methane from landfill gas is about 1.56 tons $CO_{2eq}$/ton MSW. So, the total $CO_{2eq}$ emitted is 1.56 (from $CH_4$) plus 50% of 0.346 (from $CO_2$) resulting in 1.73 tons of $CO_{2eq}$ per ton of MSW. Capital costs include site development and construction costs.

Based on the estimated obtained from the study carried out by Eilrich et al. [13], a 78.9 - acre landfill site with a total capacity of 13,64,000 tons will cost about 11.5 to 17.1 dollars per ton. The study also reveals information's regarding the operation and monitoring cost, closure cost, post-closure care cost. The O&M cost per ton is assumed to range from 19.8 to 36.2 dollars. O&M cost increases with a decrease in the size of the landfilling site. For conventional sanitary landfilling technique without energy recovery, the only form of revenue is the gate fee. The landfill gate fee is assumed to be $45/ton. Table 2 below summarizes the data used for calculating the carbon mitigation cost of conventional sanitary landfilling technique which is considered the baseline of the mitigation study highlighted in this manuscript.

Table 2. Sanitary landfilling data summarization

| Avoided GHG per ton of material (MTCO2e) | 0 | | | |
|---|---|---|---|---|
| Cost | Highest | Lowest | Mean value | Standard deviation |
| Capital cost ($/ton) | 17.10 | 11.50 | 14.30 | 2.80 |
| O & M cost ($/ton) | 36.20 | 19.80 | 28.00 | 8.20 |
| Revenue ($/ton) | 45.00 | | | |

### *3.1.2. Sanitary landfilling with gas collection and flaring: (mitigation option)*

The $CO_{2eq}$ of methane emitted from sanitary landfilling with gas collection and flaring technique per ton of MSW is about 1.56 tons. Assuming 50% of the landfilling gases (LFG) is tapped and utilized effectively. Assumptions are not made for the total LFG emitted due to delays and leaks that exist in the open landfilling system. The loss of methane is calculated to be 0.78 tons of $CO_{2eq}$ per ton of MSW. In addition to this, the direct $CO_2$ emissions are about 0.17 tons/ton of MSW, leading to the total 0.95 tons $CO_{2eq}$/ton of MSW emitted. Compared with the conventional sanitary landfilling technique (baseline), the $CO_{2eq}$ emissions is reduced by 0.78 $CO_{2eq}$ tons/ton of MSW in sanitary landfilling with gas collection and flaring technique. Capital costs include the fee of designing and engineering the plant, getting permits by ensuring site readiness and establishing the basic utilities, hardware, start-up expenses. These expenses can fluctuate depending upon a few outlined factors of the gas accumulation framework [14]. Assuming the site has the same capacity as the baseline technique, the total capital cost for the LFG collection and flare system would be over 10 million. Calculating the expense per ton the figures sum up to $1.48 per ton of MSW, resulting in the total capital cost is about $13 to $18.6 per ton of MSW. Operation and maintenance cost, in this case, includes damage to parts and material of the system, labour, utilities, financing costs and taxes which accumulates to $0.26 per ton of MSW. Using the per ton base rule, the total O&M cost is calculated to be about $20.1 to $36.8 per ton of MSW with reference to the baseline. The landfill gate fee ranges from $24/ton to $91/ton, so in this study, an average value of $55/ton is assumed to be the gate fee. According to the WTE guidebook, the value of credits per ton of avoided CER is estimated to be US$16. As noted above, the $CO_{2eq}$ reduced per ton of MSW for sanitary landfilling with LFG collection and flaring is about 0.78 $CO_{2eq}$ tons/ton of MSW. The conservative value of US$ 12.48 per ton of MSW was used for this technique. Table 3 below summarizes the data used for calculating the carbon mitigation cost of sanitary landfilling with LFG collection and flaring.

Table 3. Sanitary landfilling with gas collection and flaring data summarization

| Avoided GHG per ton of material (MTCO2e) | 0.78 | | | |
|---|---|---|---|---|
| Cost | Highest | Lowest | Mean value | Standard deviation |
| Capital cost ($/ton) | 18.60 | 13.00 | 15.80 | 2.80 |
| O & M cost ($/ton) | 36.80 | 20.10 | 28.50 | 8.35 |
| Revenue without CER($/ton) | 55.00 | | | |
| Revenue with CER($/ton) | 67.50 | | | |

### 3.1.3. Sanitary landfilling with electricity generation (mitigation option)

Assuming 50% of the landfilling gas is collected and utilized for electricity generation, the total $CO_{2eq}$ emitted in this technique is 0.95 tons/ton of MSW and the reduced $CO_{2eq}$ emissions compared with a baseline which is about 0.78 $CO_{2eq}$ tons/ton of MSW similar to the previous technique. According to USEPA landfill methane outreach program, capital costs of a 3-MW engine project without LFG collection and the flaring system would be about $53,06,874. Including the costs for energy generation equipment and the interconnection equipment resulting in an evaluated capital cost of about $16.9 to $22.5 per ton of MSW [14]. O&M costs for a 3-MW engine project without LFG collection and the flaring system is considered to be $566786 based on the values obtained from the previous study, so the O&M cost is about $20.5 to $37.2 per ton of MSW. In this technique, the sales of electricity is another important form of income to the system which has to be considered when estimating the revenue of the system. The landfilling gas to energy value is about 0.05 to 0.1 MWh for per ton of MSW. If the market electricity price to be $0.032 per kWh, the revenue of the generated electricity is about 1.6 to 3.2 dollars per ton of MSW. For the mitigation study considered in this paper, the average number of $2.4/ton is used. The landfill gate fee of sanitary landfills with electricity generation in the U.S. ranges from $24/ton to $91/ton. We assume the average gate fee of $65/ton for calculations in this mitigation study. The estimation of credits of CER per ton is assessed at US$16. As noted above, the $CO_{2eq}$ reduced per ton of MSW for sanitary landfilling with LFG electricity generation is about 0.78 $CO_{2eq}$ tons/ton of MSW. So, in this case, US$ 12.48 per ton of MSW was used for the mitigation study. Inferences obtained from the literature prove that the use of non-conventional energy is considered as a major contribution towards the leap to 100% sustainable energy [15]. Table 4 below summarizes the data used for calculating the carbon mitigation cost of sanitary landfilling with electricity generation.

Table 4. Sanitary landfilling with electricity generation data summarization

| Avoided GHG per ton of material (MTCO2e) | 0.78 | | | |
|---|---|---|---|---|
| Cost | Highest | Lowest | Mean value | Standard deviation |
| capital cost ($/ton) | 22.50 | 16.90 | 19.70 | 2.80 |
| O & M cost ($/ton) | 37.20 | 20.5 | 28.85 | 8.35 |
| Revenue without CER($/ton) | 67.40 | | | |
| Revenue with CER ($/ton) | 79.90 | | | |

### 3.1.4. Conventional WTE: (mitigation option)

Assuming dry organics sum to be 60% of biomass results about the 417 kg (2.86 kmol) of $C_6H_{10}O_4$/ton of MSW for the calculation. The amount of $CO_2$ emitted would be 17.16 kmol and 0.755 tons/ton MSW. Thus, the directly reduced $CO_2$ compared with the baseline is about 0.98 tons/ton of MSW. The total avoided GHG for per ton of mixed metal is 1.741 MTCO2e compared with sanitary landfilling. So, the GHG benefits from metal recovery is 0.045tons/ton of MSW * 1.741 MTCO2e /ton=0.078 MTCO2e /ton of MSW. Adding them together, the total reduced $CO_2$ compared to the baseline of 1.06 tons/ton of MSW. A mid-go plant of 160,000 tons yearly limit may cost from US$80 million ($500 per ton of yearly limit) to US$120 million ($750 per ton of annual capacity). Assuming WTE plant has a life period of WTE plant to be twenty years, the estimated cost for per ton MSW processed would be $25 to $37.5 dollars. O&M cost typically expanded with the diminishing of the WTE plant estimate, which is from the US $32/ton of MSW to $47/ton of MSW [12]. Assuming that 0.55MWh of electricity is produced per ton of MSW, adding up to about $17.6 per ton of MSW at the market electricity price of $32/MWh.

$$C_6H_{10}O_4 + 6.5\ O_2 = 5\ H_2O + 6\ CO_2 \quad (5)$$

The WTE gate fee is assumed to be $25/ton to $98/ton. The average number of $61.5 is used for the mitigation study discussed in this manuscript. The anticipated lessening in ozone-depleting substance emissions due to the WTE task would be 1.06 tons of carbon dioxide per ton of MSW, in contrast with sterile landfilling. As indicated by the WTE Guidebook, the estimation of credits of carbon outflows per ton CER is evaluated to be at US$17. Roughly 45 kilograms of metal could be recycled from this technique resulting in an additional revenue from sales of metals recovered from the ash. Utilizing an expected cost of US$500 per ton of scrap metals, the WTE system would have an income of US$22.5 per ton of MSW combusted. Table 5 below summarizes the data used for calculating the carbon mitigation cost of WTE plant.

Table 5. Waste to energy data summarization

| Avoided GHG per ton of material (MTCO2e) | 1.06 | | | |
|---|---|---|---|---|
| Cost | Highest | Lowest | Mean value | Standard deviation |
| capital cost ($/ton) | 37.50 | 25.00 | 31.25 | 6.25 |
| O & M cost ($/ton) | 47.00 | 32.00 | 39.50 | 7.50 |
| Revenue without CER($/ton) | 101.60 | | | |
| Revenue with CER ($/ton) | 118.60 | | | |

### *3.1.5. MBT plus WTE: (mitigation option)*

The total avoided GHG for per ton of MSW that was recycled and composted in the MBT plant is about 0.25 MTCO2e. When one ton of MSW goes into the MBT, on an average 0.55 tons residues go to WTE. Since one-ton MSW in WTE will save 1.06 MTCO2e compared with sanitary landfilling, the GHG from WTE part would be 0.55tons * 1.06 MTCO2e /ton of MSW = 0.58 tons of MTCO2e. Adding up two parts GHG scheme of this technique, the total savings would be about 0.83 MTCO2e /ton of MSW in MBT plus, WTE facility. The capital cost for the MBT ($400 per ton of MSW) plus WTE ($600) option should be around $400 + $600 * 55% = $730 per ton. Assuming lifetime of 20 years, the total site capacity for the whole life of MBT plus WTE plant, the cost for each ton MSW processed is about 36.5 dollars. The O&M cost of this facility ranges from $36.66 to $51.66 per ton MSW. Recyclables and decomposable constitute 27.3% of the total MSW in MBT plant. According to the percentage of different recyclables and the secondary market price per ton MSW goes to the integrated system, the revenue is $96.42/ton MSW. An MBT plant will have the gate fee from $50-55 per ton MSW [16]. Also using 61.5 dollars per ton MSW as the gate fee for WTE, 55% MSW will go to WTE after MBT, for one-ton MSW, the estimated gate fee would be about $86.3 per ton of MSW. Matero facilities typically provide 0.39 MWh/ton electricity although WTE plant of this capacity (500 metric tons/day) typically provides to the grid 0.55 MWh per metric ton. Also, assuming the electricity price is $0.032/kWh, the revenue should be about 390 kWh/ton of MSW * $0.032/kWh = $12.48/ton. Carbon credits resulting in the estimation of credits per ton of maintained a strategic distance from CER is evaluated at US$16. So, for this technique, the moderate estimation of US$13.28 per ton of MSW was used for the mitigation study. Table 6 below summarizes the data used for calculating the carbon mitigation cost of MBT plus WTE plant.

Table 6. MBT plus WTE data summarization

| Avoided GHG per ton of material (MTCO2e) | 0.83 | | | |
|---|---|---|---|---|
| Cost | Highest | Lowest | Mean value | Standard deviation |
| capital cost ($/ton) | 36.50 | 36.50 | 36.50 | 0.00 |
| O & M cost ($/ton) | 51.70 | 36.70 | 44.20 | 7.50 |
| Revenue without CER($/ton) | 106.10 | | | |
| Revenue with CER ($/ton) | 119.40 | | | |

## 4. Results and Discussions

In this study, two kinds of total revenue were evaluated: with and without CER is considered when breaking down the mitigation cost. As illustrated in the above section, all the last four mitigation options have corresponding carbon reductions cost comparing the baseline value. The revenue without CER can represent more common situations, however it more valuable to see what happens for carbon mitigation cost if CER is included. The overall summarization of the mitigation and cost benefits analysis for five scenarios are illustrated in Table 7 below.

Table 7. Summary of cost and price assumptions for different waste management technologies

| **Waste management methods** | **Capital Cost ($/ ton)** | **O&M Cost ($/ton)** | **Revenue without CER ($/ton)** | **Revenue with CER ($/ton)** | **GHG reduced (MTCO2e /ton)** |
|---|---|---|---|---|---|
| Sanitary landfilling (baseline) | 14.30 | 28.00 | 45.00 | 45.00 | 0.00 |
| Sanitary landfilling with LFG collection and flaring | 15.80 | 28.50 | 55.00 | 67.50 | 0.78 |
| Sanitary landfilling with electricity generation | 19.70 | 28.85 | 67.40 | 79.90 | 0.78 |
| Waste to energy | 31.25 | 39.50 | 101.60 | 118.60 | 1.06 |
| MBT plus WTE | 36.50 | 44.20 | 106.10 | 119.40 | 0.83 |

### *4.1. GHG emissions of five scenarios*

Fig. 3. represents the visualization of GHG reductions for five techniques. WTE has the highest GHG reduction overall. The second highest GHG reductions are from MBT plus WTE technique, followed by two kinds of landfilling with energy recovery has the least GHG reductions. Surprisingly, the GHG reduction of MBT plus WTE plants is lower than WTE plant, reasons for this could be only 7.3% of MSW recycled in MBT, and there are certain parts of MSW being composted that would also emit methane to the atmosphere.

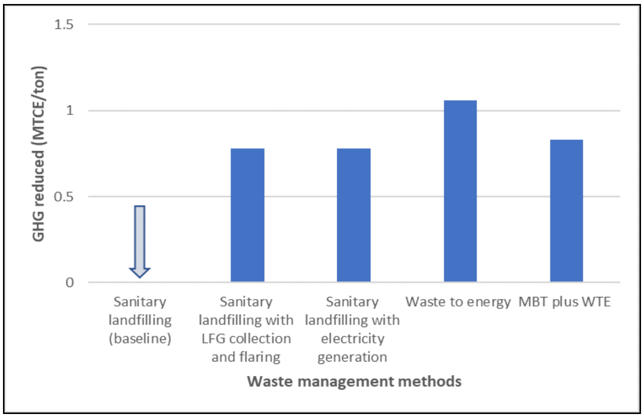


Fig. 3. Graphical representation of GHG reduction.

### *4.2. Cost benefits analysis of different waste management options*

Considering the net profits of each technique, as shown in Figure 4, all of them have a positive net profit, which means their revenues exceed the costs. WTE has the highest profits, MBT plus WTE ranks the second highest, then three kinds of landfilling have relatively lower profits.

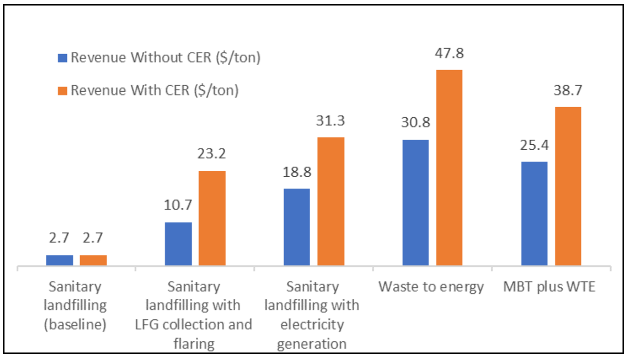


Fig. 4. Net Profits Comparison Among Five Waste Management Techniques.

### *4.3. Carbon mitigation cost analysis*

Both the GHG benefits and economics of waste mitigation options are considered for the study, figure 5 is the representation of similar relief measures that show the financial aspects and in addition the specialized benefits of reducing GHG outflows. This chart is built by demonstrating the GHG reduction cost of waste division alternatives (vertical line) as a component of their GHG diminished (even line) and putting in moderation measures in rising request of cost-adequacy. This graph reflects the economic position when their environmental benefits are considered at the same time. This information is more vital for decision-makers to decide on which is the most effective and efficient method for small-scale MSWM technique.

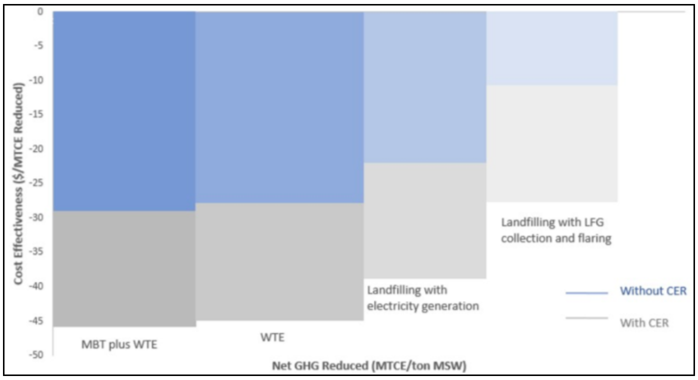


Fig. 5. Carbon mitigation cost (with and without CER) of four waste management techniques compared with baseline.

Different carbon mitigation measures have varied economical influences based on the GHG emission impact. MBT plus WTE has the highest profits, which is 27.34 dollars for reducing one metric ton of carbon dioxide equivalent without considering CER. WTE is the second most effective one which not only takes out the natural effects of landfill waste and mitigates an earth-wide temperature boost but also has the highest profits from the energy recovery. Since not 100% of landfills are equipping sanitary landfill with gas collection and electricity generation systems, the most environmentally friendly and economical profitably of WTE is encouraged for the future setups. Overall, the performance of carbon mitigation costs for waste management options discussed in this study obeys the waste management hierarchy sequence indicating the significance of the study highlighted in the manuscript.

## 5. Conclusion

The main objective of the study presented in the manuscript is to perform cost-benefit analysis and mitigation cost breakdown of the different waste management techniques to identify the optimum technique suited for small-scale MSWM systems. From the results obtained from the case study and mitigation analysis, it is clear that the hybrid MBT plus WTE approach appears to be the best option considering the five techniques considered in the study, although conventional WTE has a higher impact on GHG reduction than the MBT plus WTE. Few highlights of the observations obtained from the study are; 1) MBT plus WTE or WTE would be the best suited for a small-scale MSWM setup considering its impact on the total revenue and carbon mitigation cost. 2) Landfilling with energy recovery has a better environment and economic performance than landfilling without any energy recovery. 3) Reduced GHG emission and cost of energy sales from LFG with electricity generation make it more impact full than LFG collection and flaring. 4) Carbon mitigation cost ranks the techniques in the same level as indicated in the waste management hierarchy no matter considers CER or not. These observations obtained from the study are useful and essential for decision makers and planning authorities to set up small-scale (MSWM) waste management plants which indicates the significance of the study presented.

## References


[1] Hoornweg D and Bhada-Tata P. What a waste: a global review of solid waste management, 2012.

[2] Wilson DC et al., Global waste management outlook. UNEP, 2015.

[3] Morrison GL. Managed composition of waste-derived fuel, ed: Google Patents, 1999.

[4] Kothari R, Kumar V, Panwar N, and Tyagi V. Municipal solid-waste management strategies for renewable energy options. Sustainable Bioenergy Production. CRC Press, Taylor & Francis, Boca Raton, vol. 267, 2014.

[5] Mohee R, Mauthoor S, Bundhoo ZM, Somaroo G, Soobhany N, and Gunasee S. Current status of solid waste management in small island developing states: a review. *Waste Management*, 2015; 43: 539-549.

[6] Squires CO. Public participation in solid waste management in small island developing states, Caribbean Development Bank, Barbados, 2006.

[7] Morrison R. and Munro A. Waste management in the small island developing states of the South Pacific: an overview. *Australian Journal of Environmental Management*, 1999; 6(4): 232-246.

[8] Mohee R and Mudhoo A. Energy from biomass in Mauritius: overview of research and applications. in Waste to Energy: Springer, 2012, pp. 297-321.

[9] Pariatamby A and Tanaka M. Municipal solid waste management in Asia and the Pacific Islands. *Environmental Science*, Springer, Singapore, 2014.

[10] Kaufman SM and Themelis NJ. Using a direct method to characterize and measure flows of municipal solid waste in the United States. *Journal of the Air & Waste Management Association*, 2009; 59(12): 1386-1390.

[11] Ibrahim N. and Kennedy C. A methodology for constructing marginal abatement cost curves for climate action in cities. *Energies*, 2016; 9(4): 227.

[12] Themelis NJ, Kim YH, Brady MH. Energy recovery from New York City municipal solid wastes. *Waste Management & Research*, 2002; 20(3): 223-233.

[13] Eilrich FC, Doeksen GA, and Van Fleet H. An economic analysis of landfill costs to demonstrate the economies of size and determine the feasibility of a community owned landfill in rural Oklahoma. in *Proc. of the Southern Agricultural Economics Association Annual Meeting*, Alabama, 2003, pp. 1-5: Citeseer.

[14] Wilson DC, Rodic L, Scheinberg A, Velis CA, and Alabaster G. Comparative analysis of solid waste management in 20 cities. *Waste Management & Research*, 2012; 30(3): 237-254.

[15] Tareen W, Anjum Z, Yasin N, Siddiqui L, Farhat I, Malik S, Mekhilef S, Seyedmahmoudian M, Horan B, Darwish M., and Aamir M. The prospective non-conventional alternate and renewable energy sources in Pakistan—A focus on biomass energy for power generation, transportation, and industrial fuel. *Energies*, 2018; 11(9): 2431.

[16] Adewuyi AO and Awodumi OB. Biomass energy consumption, economic growth and carbon emissions: Fresh evidence from West Africa using a simultaneous equation model. *Energy*, 2017; 119: 453-471.