Sustainability Analysis of Anaerobic Digestion Systems for Decentralized Waste Management

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Abstract: - Life cycle assessment (LCA) and life cycle costing (LCC) analyses were utilized to assess decentralized anaerobic digestion (AD)-based solid waste management (SWM) plans for a remote community. A hypothetical developing community of 20,000 habitants was selected with an average municipal solid waste (MSW) generation of 0.51 kg/capita/day. Sustainable SWM is needed to ensure both the environmental and economic aspects. In order to exploit the resource value of the high food fractions in developing countries, sustainable waste management alternatives have been emerged and compared to the commonly used SWM scenario (landfills). The scenario included, collection and transportation of waste, material recovery facility (MRF), AD, and landfilling processes. WRATE software databases were used to obtain data for the life cycle inventory (LCI). The functional unit has been selected as the management of 1 ton of MSW for a study period of 20 years. The scenarios were evaluated via the CML 2001 impact assessment method covering 6 categories including climate change, eutrophication potential, acidification potential, freshwater aquatic ecotoxicity, human toxicity, and resource depletion. The findings revealed that the proposed strategy improved the life cycle environmental performance in all impact categories and resulted in significant economic savings.

Keywords: - Anaerobic Digestion; Organic Waste Management; Life Cycle Assessment; Life Cycle Costing, Eco-efficiency
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1 Introduction

Municipal solid waste (MSW) landfills generate methane through the anaerobic decomposition of organic waste. According to the 5th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), methane has 28 times the global warming potential (GWP) of carbon dioxide over a 100-year time horizon, [1]. A preliminary analysis carried out by the National Oceanic and Atmospheric Administration (NOAA) indicated 17 parts per billion (ppb) annual increase in atmospheric methane during the year 2021, the largest increase in methane concentration since 1983 [2]. It is produced from MSW by a consortium of microorganisms that decompose complex organic molecules sequentially through hydrolysis, fermentation, acetogenesis, and methanogenesis. Biogas-to-energy systems can be implemented on-site to collect and convert methane into energy, reducing the amount released into the atmosphere. Recycling, climate change, and socioeconomic benefits can be achieved with small-scale biowaste treatment plants because of low transportation costs, adaptability to mass changes, high-quality products, the need for simple technology, smaller facilities, reduced treatment costs, and shorter payload distances, [3].

Life cycle assessment (LCA) is a systematic framework that evaluates the environmental impacts of different projects, systems, and products. In the SWM context, LCA would account for the interlinks between solid waste management and the economic sector. LCA has been deployed as a useful decision-making tool in various waste management research studies. Banar et al., (2009) used LCA to investigate five different alternative scenarios compared to the current waste management system in Eskisehir, Turkey. The examined scenarios included transportation and collection of waste, material recovery facility, recycling, composting, incineration, and landfilling. It was found in their study that the composting scenario is the most environmentally favorable alternative. Moreover, Finnveden et al., [4] discussed the applicability of the LCA tool in SWM by identifying limitations of the LCA methodology and comparing landfilling, recycling, incineration, digestion, and composting scenarios based on previous case studies. In their study incineration was found to be a better SWM solution compared to landfilling in terms of using biomass as fuel which can reduce greenhouse gas emissions. Coventry et al. (2016) also utilized LCA to compare four different solid waste treatment scenarios including dry-tomb landfill, landfill gas to energy, advanced thermal recycling, and gasification in the U.S. Cities. The findings revealed that the majority of the environmental impacts were attributed to thermal treatment strategies. Another study done by [5] investigated the potential of improving SWM by examining several scenarios including landfill in combination with an expanded system combining mechanical separation of recyclable fractions, anaerobic digestion (AD) of the organic fraction of MSW, and thermal treatment of the residual waste. The results of this study show that implementing recycling practices enhanced the overall environmental performance. Few more studies evaluated the impacts of utilizing small-scale SWM technologies. For example, [6] assessed the impacts of SWM scenarios (including open dumps and small-scale incinerators) implemented in Greenland. The results revealed that the detrimental effects were mainly due to air emissions from the incinerators, whereas other impacts such as global warming potential and acidification were relatively low as a result of serving a small population (about 56,000 per capita). Other studies only discussed the optimization of the different SWM scenarios applied in small-scale settings, [7], [8].

Few studies have examined the combined environmental and economic impacts of SWM systems in terms of the life cycle approach. A study by [9] evaluated different MSW management scenarios, including AD, incineration, composting, recycling, and landfilling in different Swedish municipalities. The results revealed the applicability of combined LCA and LCC methods, where both analyses revealed higher environmental and economic costs of landfilling. Similarly, [10] utilized LCA and LCC to investigate the impacts of different SWM strategies, particularly paper waste. The findings revealed that recycling is the optimum scenario in terms of environmental analysis which was reinforced by the economic assessment results. Moreover, [11] studied the viability of an AD plant for the collection and treatment of different waste streams (e.g., mixed solid waste, biowaste, and glass). The results revealed the energy recovery potential and environmental benefits of the AD system. The biogas plant resulted in total revenue of USD 178,000/year. In addition, the recycling of the digestate for agricultural applications was confirmed via the characterization of the digestate which showed the viability of composting. Another case study in Istanbul, Turkey was conducted to evaluate the economic and environmental burdens of solid waste management vis examining 114 scenarios using a mathematical model [12]. The results suggested the implementation of AD and incineration strategies as a long-term sustainable solution in terms of cost and greenhouse gas emissions.

In order to improve the waste management practices for decentralized systems, various sustainability perspectives should be considered. Based on the reviewed literature, there is a lack of LCA studies that evaluate solid waste management in small communities. Based on the conducted literature review, no eco-efficiency study has been conducted on SWM of remote communities. Hence, the main objective of this paper is to present a thorough environmental and financial assessment of decentralized AD-based municipal solid waste management scenarios along with an eco-efficiency analysis by integrating LCA and life cycle costing assessment (LCCA) frameworks. The selected waste management facilities involve an anaerobic digester, material recovery facility (MRF), and landfill (current scenario). The study was conducted for a small community over a 20-year assessment period. The examined waste management scenarios are compared to similar LCA and waste-to-energy-based studies from the literature. This research study provides a framework for decision-makers to design sustainable and integrated solid waste management (ISWM) strategies to improve public health and economies considering local conditions.

2 Methodology

The following subsections include the methodological approach followed to carry out this study.

2.1 Framework Application

In order to assess the feasibility of decentralized AD-based waste management scenarios in developing countries, a hypothetical community of 20,000 inhabitants is selected as a case study. Life cycle of the examined management plans is evaluated from environmental and financial perspectives over an operational period of 20 years. The waste compositions of the study area are compiled from the literature as the average data of several developing countries; where organic, plastic, textile, paper and cardboard, and miscellaneous wastes comprised 50, 15, 10, 10, and 15% of the total MSW respectively, [13]. Fig. 1 shows the examined waste management scenarios of this study. The proposed waste management plan includes collecting organics and non-organics in dual bins where organic waste is processed in AD, and non-organics are dispatched to MRF since material recycling is a substantial pillar of sustainable waste management, [14]. The initial participation rate of organic bins was assumed as 20% and growing annually at a rate of 5%. The resulting digestate and baled materials are marketed where the rest is landfilled. The proposed decentralized framework was compared to the common waste management practice in developing countries of landfilling MSW from several sustainability perspectives.

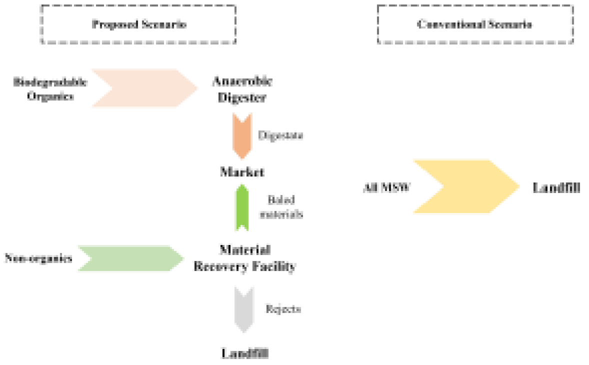

Fig. 1 Waste streams of the selected management strategies.

2.2 Life Cycle Assessment

2.2.1 Goal and Scope

LCA is a powerful method to evaluate the environmental impacts associated with the different waste management strategies. This study intends to compare the environmental performance of the selected scenarios throughout the 20 years in terms of LCA. The comparative analysis was carried out with a reference to a functional unit which is the management of 1 ton of MSW generated in the remote community. The management includes the collection, transportation, recovery, treatment, and/or disposal of the generated MSW. WRATE V4 software is utilized to evaluate the LCA of the selected waste management systems.

2.2.2 Life Cycle Inventory (LCI)

The data used in this study is compiled from literature and WRATE database. WRATE utilizes the Ecoinvent version 1.2 and compiled data by environmental resource management (ERM). The inventory was obtained from the software and utilized in life cycle impact assessment (LCIA) computations of the examined systems.

2.2.3 Life Cycle Impact Assessment (LCIA)

Environmental impact of the selected SWM scenarios was evaluated using the problem-oriented approach embedded in WRATE software. CML 2001 methodology was utilized to explore and analyze the environmental impacts on the main indicators, [15]. Those impact categories involve global warming potential (GWP) (kg, CO_2-Eq), acidification (kg, SO_2-Eq), eutrophication (kg PO_4-Eq), freshwater ecotoxicity (kg, 1,4-dicholorobenzeneEq), resource depletion (kg, Sb-Eq), and human-related impacts such as carcinogens and non-carcinogens (kg, 1,4-DCB-Eq), [16]. GWP is mainly associated with GHG emissions and eutrophication, whereas freshwater toxicity is concerned with pollutants and toxic matter released from waste management processes. Since harmful substances directly impact humans, they are usually characterized using a human toxicity indicator. Moreover, the resulting impacts of using non-renewable sources of energy such as fossil fuels are represented by the resource depletion category.

2.3 Life Cycle Costing (LCC)

The financial feasibility of the examined waste management scenarios is assessed and compared through conducting an LCC analysis over the assessment period of 20 years. Net present value (NPV), the present worth of all costs and revenues for the examined systems, is computed using Equation 1 as follows, [17]:

$$NPV = \sum[(CI_t - CO_t) \times (1+i)^{-t}] \qquad (1)$$

Where *NPV* is the net present worth (USD), CI_t is the cash inflow in t years (USD), CO_t is the cash outflow in *t* years (USD), *i* is the discount rate, and *t* is the assessment years. The cash outflow includes capital expenditures (CAPEX) as well as annual operational and maintenance costs (OPEX). Capital costs comprise installation, infrastructure, and civil works, while OPEX includes all annual direct and indirect overhead costs. The CAPEX and OPEX were mainly compiled from the literature as shown in Table 1. On the other hand, cash inflow includes the annual revenues from selling baled materials and digestate at market, as well as electricity sales which depend on energy generation potential of AD facility; retrieved from [18].

Table 1 Capital expenditure (CAPEX), and operational & maintenance expenditure (OPEX) of the selected facilities.

Facility	CAPEX	Unit	OPEX	Unit	Reference
MRF	30	USD/ton	3	USD/ton	Tchobanoglous and Kreith, 2002
AD	220	USD/ton	10	% of the CAPEX	IRENA, 2015
Landfill	20	USD/ton	2	USD/ton	Movahed et al., 2020

2.4 Eco-efficiency Analysis

The selection of an optimum alternative and the identification of system trade-offs can be accomplished through an eco-efficiency analysis. Such analytical framework functions by integrating LCC and LCCA results, which are then plotted into a single portfolio [22]. The ratio method is the most commonly used approach to determine the eco-efficiency of a system or a product [23]–[25]. In this study, the ratio method, which is defined as the ratio of the economic indicator to the environmental performance, is employed for the examined SWM plans, as shown in Equation 2 [25]:

$$Eco-efficiency=\frac{Environmetal\ Performance}{Economic\ Value} \quad (2)$$

The environmental indicator in this study was retrieved from the LCA WRATE software; represented by a normalized and weighted single value aggregating all the midpoint categories. On the other hand, NPV was utilized as the economic indicator for the examined scenarios. An eco-efficiency portfolio combining the environmental and economic scores was plotted for the selection of the most eco-efficient system taking into consideration the trade-off among the studied alternatives.

3 Results and Discussion

3.1 Life Cycle Assessment

Table 2 summarizes the material and energy recovery potential from the examined alternatives retrieved from WRATE software. The energy and material recovery potential of the decentralized AD system was significantly higher than the conventional system. This could be due to the higher energy generation efficiency and lower gas leakage potential of AD systems. Moreover, the amount of waste landfilled in the conventional system was 5 times higher than the proposed system, which would impose higher environmental risks.

Table 2 Flow streams of the examined management strategies.

Indicator	Unit	Conventional	Proposed
Biodegradable Waste Landfilled	ton	2,978	266
Energy Recovered	MJ	1,982,811	3,032,441
Waste Composted	ton	-	1,862
Waste Landfilled	ton	3,723	715
Waste Recycled	ton	-	1,361

Table 3 summarizes the environmental impacts of the examined scenarios on different assessment categories. Overall, the proposed scenario showed better environmental performance in all categories except freshwater aquatic ecotoxicity. The proposed scenario decreased the climate change impacts significantly by more than 1,298 Mg CO_2-eq. Similarly, the environmental performance of the proposed AD-based scenario was enhanced by 732, 96, 604, and 302% in the following categories: acidification potential, eutrophication potential, human toxicity, and depletion of abiotic resources, respectively.

Table 3 Impact categories of the examined waste management plans.

Impact Category	Conventional	Proposed
Climate Change (kg CO_2-Eq)	912,741	-385,644
Acidification Potential (kg SO_2-Eq)	245	-1550
Eutrophication Potential (kg PO_4-Eq)	1,439	49
Freshwater Aquatic Ecotoxicity (kg 1,4-DCB-Eq)	-41.2	46531
Human Toxicity (g 1,4-DCB-Eq)	-6,475	-45,617
Depletion of Abiotic Resources (kg antimony-Eq)	-2,279	-9,178

3.2 Life Cycle Costing Analysis

A financial feasibility analysis was carried out for the selected waste management systems. Table 4 below summarizes the obtained results from the LCC analysis for the 20 years study period. In comparison to the conventional scenario, the integration of decentralized MRF and AD in the proposed systems had a fourfold improvement to the economics. This can be attributed to the revenues from the sales of baled materials in MRFs and digestate in AD. Although anaerobic digesters have high capital costs, combining such a facility with MRF would increase the cost-savings due to the high revenue from selling the generated electricity associated with AD. MRF was incorporated in the proposed scenario as material recovery plays an essential role in sustainable waste management.

Table 4 Life cycle costs for the selected waste management scenarios.

Scenario	**CAPEX (USD)**	**Annual Cash Flow (USD)**	**Total NPV (USD)**
Proposed	1,097,727	979,834	-117,894
Conventional	887,396	354,958	-532,437

Fig. 2 depicts the cumulative NPV and the expected payback periods for the selected management scenarios over the 20 years assessment period. The payback periods for the proposed system were found to be around 8 years, while the conventional scenario had no payback period as the investment was not recovered over the study period.

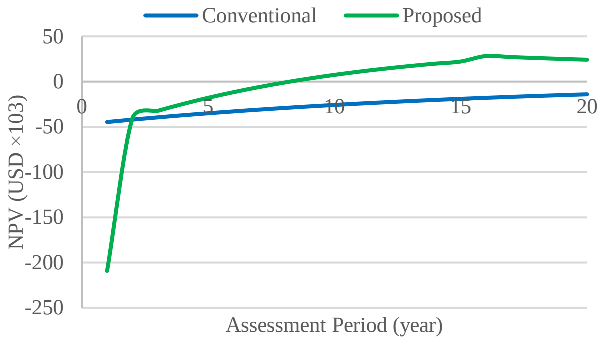

Fig. 2 Payback period analysis for the examined waste management strategies.

3.3 Eco-efficiency Analysis

The depicted results of the economic and environmental performance ratios were plotted in an eco-efficiency portfolio as illustrated in Fig. 3. The scenarios can be evaluated in terms of low and high eco-efficiency according to the relative eco-efficiency score. The conventional waste management system was characterized by high environmental impacts and significant economic losses. On the other hand, the decentralized AD-based system has proven to be eco-efficient compared to the conventional scenario. The eco-efficiency index diagram orders the alternatives from the highest (top) to the lowest (bottom) eco-efficiency. Therefore, based on the eco-efficiency results the proposed strategy is the most eco-efficient alternative in terms of economic viability and environmental performance.

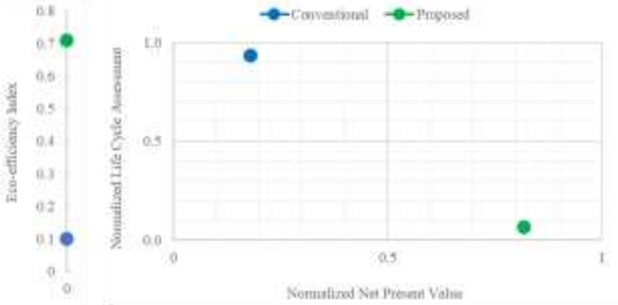

Fig. 3 Eco-efficiency portfolio of the examined waste management scenarios.

4 Conclusion

The high fraction of organic wastes in developing countries demands sustainable alternatives for organic waste management due to the environmental pollution and health risks imposed by the conventional management system. This research aims to propose and evaluate decentralized AD-based waste management scenarios from financial and environmental perspectives. The proposed scenario includes collecting the MSW in dual bins where organic wastes are processed in decentralized AD systems and non-organic wastes are dispatched in MRFs. This system was compared to the conventional practice of landfilling the MSW from life cycle environmental and financial perspectives. The LCA results revealed that the proposed system can improve the environmental performance in all impact categories, including climate change, acidification potential, eutrophication potential, human toxicity, and depletion of abiotic resources. However, the environmental impacts on freshwater ecotoxicity increased significantly. Similarly, The LCC findings proved that the proposed system is financially more feasible compared to landfilling. The findings of LCA and LCC were integrated through an eco-efficiency framework to highlight the optimum scenario that meets the environmental and economic needs simultaneously. The analysis revealed that the decentralized AD-based system is the most eco-efficient waste management plan. Future studies can incorporate a social assessment to the current study to further comprehend the analysis.

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