Journal of Engineering in Industrial Research
2025, Volume 6 Issue 4

Original Research Article

Comparative Life Cycle Economic Assessment of Treatment Technologies for Converting Municipal Solid Waste into Bio-Energies

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Citation Z. Alidoosti, A. Sadegheih, M.S. Pishvaee. Comparative Life Cycle Economic Assessment of Treatment Technologies for Converting Municipal Solid Waste into Bio-Energies. *J. Eng. Ind. Res.* **2025**, 6 (4):352-364.

https://doi.org/10.48309/JEIRES.2025.517322.1199

Article info:
Submitted: 2025-04-16
Revised: 2025-07-17
Accepted: 2025-08-07
ID: JEIRES-2504-1199

Keywords:
Bioenergy; Economic assessment; Treatment technology; Life cycle.

ABSTRACT

Life cycle economic assessment serves a vital role in evaluating sustainability across various industries. This study aims to conduct a comparative life cycle economic analysis of different conversion technologies to identify the most viable options for treating Municipal Solid Waste (MSW). It specifically examines six different scenarios based on these conversion technologies: anaerobic digestion for heat and electricity, anaerobic digestion for household biogas, anaerobic digestion for fuel gas, pyrolysis for electricity, fermentation for bioethanol, and landfill gas collection for household use. A case study was conducted in Aradkooh, Iran. The results reveal that the landfill gas collection scenario is the most economically viable option, with a net present value (NPV) of $5.28 million. In contrast, the fermentation scenario shows an NPV of -$1,209 million, highlighting its significant economic shortcomings. The sensitivity analysis demonstrates that the most influential factors in enhancing the NPV are the operational efficiency of the conversion technologies and the market prices for bio-energies. It is highly recommended that stakeholders secure sufficient funding to improve treatment technology readiness. Additionally, the government should take proactive steps to attract venture capital in this sector by developing strong infrastructure and offering compelling incentives. To promote sustainable decision-making, it is essential to conduct comprehensive environmental and social assessments along with economic evaluations before implementing any conversion technologies.

Introduction

Numerous studies have investigated innovative approaches for managing municipal solid waste (MSW), particularly concentrating on the economic assessment of technologies that convert MSW into energy. In this section, we review a techno-economic assessment of the life cycle for converting MSW into energy, with emphasis on decision-making regarding viable options. Luz *et al.* [1] conducted a techno-economic assessment of gasification technology for generating bioelectricity from MSW in Brazil. The financial metrics used for evaluation included net present value (NPV) and internal rate of return (IRR). The findings showed that larger plants with higher installed power capacity are more economically viable. Salman *et al.* [2] carried out a techno-economic investigation on conversion technologies, including anaerobic digestion and pyrolysis, for producing high-quality biogas. The economic assessment of a plant with a capacity of 23,000 tons of MSW annually represented an acceptable result with a financial return rate of about six years. Based on sensitivity analysis, product price is the critical item for profitability. Yang *et al.* [3] conducted a comprehensive techno-economic feasibility study of an integrated Pyro-Combined Heat and Power plant (CHP) in the UK. Their research indicates that a proposed plant with an input capacity of 5 tons per hour could generate an impressive 4.4 MW of electricity and 5.3 MW of heat, achieving yields of 27.2% for electricity and 59.7% for heat. The estimated capital investment for this innovative facility was projected to be £6.23 million per unit of power. Importantly, the study underscores the significant role that governmental renewable incentive fees play in enhancing economic viability. Additionally, various strategic approaches can enhance the project's feasibility, including reducing electricity production costs, identifying suitable markets for bioenergy, optimizing waste management gate fees, increasing plant availability, and improving productivity. Ayodele *et al.* [4] conducted an economic and environmental assessment of biogas recovery from MSW using two technologies: anaerobic digestion and landfill gas recovery for electricity production in Ibadan City, Nigeria. The economic assessment revealed that both technologies are viable, as indicated by their positive net present values. The financial indicators analyzed in the study included the payback period, internal rate of return, and total life cycle cost. For anaerobic digestion, these indicators were approximately five years for the payback period, 19.3% for the internal rate of return, and 413.68 million US dollars for the total life cycle cost. In comparison, the landfill gas recovery method had a payback period of seven years, an internal rate of return of 23.4%, and a total life cycle cost of 288.05 million US dollars. Afrane *et al.* [5] conducted a multi-criteria decision analysis to assess the techno-economic feasibility of waste-to-energy (WtE) technologies in Ghana. The technologies analyzed included anaerobic digestion, gasification, plasma arc gasification, and pyrolysis. The study utilized a fuzzy TOPSIS method. The findings indicated that gasification technology emerged as the most viable option, while plasma arc gasification ranked lowest. Anaerobic digestion and pyrolysis were situated between these two technologies. The research suggested a hybrid approach, combining anaerobic digestion and gasification, as this combination provides a more balanced and effective solution for energy generation compared to standalone plants. Nassar *et al.* [6] examined the techno-economic feasibility of implementing WtE technologies in Egypt, taking into account the existing governmental regulations. Their analysis revealed the importance of strengthening the current WtE regulations by incorporating a gate fee, which would serve as a vital revenue stream for WtE technologies. Sajid Khan *et al.* [7] conducted an exergy-economic assessment of a proposed solar combined WtE plant. They compared its efficiency to that of a conventional WtE plant. The capacity of the incineration facility was set at 300 tons per day (t/d). The results indicated that the efficiency of the proposed innovative conversion technology is approximately 12.61% greater than that of the conventional system. This improvement is primarily due to the increased turbine inlet temperature provided by the solar system. Additionally, the electricity cost of the proposed system is 13.9% lower than that of the conventional plant. Park *et al.* [8] conducted a techno-economic analysis of eight different scenarios, which included five gasification-based, one incineration-based, and two pyrolysis-based configurations. The aim of these scenarios was to produce syngas, electricity, hydrogen, methanol, and gasoline from MSW. The findings indicated that the pyrolysis scenario for electricity generation had the highest costs, while the incineration scenario resulted in the lowest costs. The sensitivity analysis demonstrated that several factors, including production rate, annual operating time, plant capacity, and subsidies, significantly impact the economics of all scenarios. Therefore, to successfully implement the proposed WtE scenario in a specific project, it is crucial to evaluate the local subsidy landscape and the optimal facility capacity. Research on bioenergy generation indicates that the net present value (NPV) and benefit-to-cost ratio are effective economic indicators for decision-making. Additionally, a life cycle economic assessment can be a useful tool for analyzing the profits and costs associated with a bioenergy supply chain that utilizes MSW. While several studies examine the economic evaluation of technologies that convert MSW into energy, there exists a pressing need for a comparative analysis of the life cycle economic assessments of various treatment technologies that convert MSW into different forms of bioenergy and biofuels. Addressing this gap is crucial for identifying both cost-effective and efficient waste management solutions. This research assesses the economic viability of different conversion technologies throughout their entire life cycles and provides a comparative analysis among them. The technologies under consideration include: pyrolysis for electricity (P), anaerobic digestion for heat and electricity (AD1), anaerobic digestion for household gas (AD2), anaerobic digestion for fuel gas (AD3), Fermentation for bioethanol (F), and landfill gas collection for household use (LG). After examining technical feasibility studies and consulting with energy experts and biotechnologists from both the industry and academic sectors, treatment technologies were selected based on their suitability for the type of municipal solid waste in this study. The following mathematical models evaluate the total profits and costs associated with the life cycle of conversion technologies that generate bioenergy from municipal solid waste (MSW). The NPV is an essential measure of economic viability, assisting in decision-making when selecting the best option. To better understand how changes in input parameters can affect the estimated NPV results, a sensitivity analysis was conducted.

Experimental

Description of the goal and scope of the study

This study evaluates the life cycle economic of selected treatment technologies for converting MSW into different forms of bioenergy. The research was conducted at the Aradkooh site in Tehran, which serves as a collection and conversion facility for MSW. This location, situated in the southern part of the city, has been collecting waste from Tehran since 1976.

Description of scenarios

This study evaluates six conversion technologies utilized in various scenarios for generating bio-energy from MSW, as detailed in Table 1. Further data on these scenarios are provided as follow:

Scenario 1: Pyrolysis

In the pyrolysis process, there are three main sub-processes: pre-treatment, thermal conversion, and product exploitation (see Figure 1). The primary product of pyrolysis is syngas. The quantity of syngas produced is significantly affected by several factors, including reaction temperature, residence time, and heating rate [9-10]. As illustrated in Figure 1, after the drying and screening processes, MSW is then subjected to thermal processing. During thermal conversion, syngas is produced. This syngas is then used in gas turbine/combined cycle systems to generate bioelectricity. In most industrial pyrolysis operations currently in use worldwide, a temperature range of 500-550 °C is commonly applied [11].

Scenario 2: Anaerobic digestion for heat and electricity (AD1)

Anaerobic digestion(AD) is a biochemical process that converts complex organic matter into simple solvable combinations under anaerobic conditions [12-13]. The technology of anaerobic digestion(AD1) contains the sub-processes of metabolic degradation and consolidation of organic materials under anaerobic conditions, such as hydrolysis, acidogenesis, and methanogenesis, leading to the generation of biogas which is a bioenergy source [14]. According to the LCA of AD1 (see Figure 2), the biodegradable portion of the MSW is converted into biogas by anaerobic digestion. This biogas is applied for electricity generation and usage in the grid [15].

Scenario 3: Anaerobic digestion for household gas (AD2)

As mentioned in the previous scenario, the significant advantage of AD is converting organic MSW into biogas under anaerobic circumstances. The biogas is a gas mainly made up of methane and carbon dioxide. Methane is the origin of renewable energies, including electricity, household gas, and gas fuel. This scenario is designed based on AD for the generation of household gas. Figure 3 demonstrates the life cycle of this scenario [15]. This process is the same as the previous process, with the difference that the output biogas needs to be upgraded to generate household gas [16].

Scenario 4: Anaerobic digestion for fuel gas (AD3)

Designing the AD3 process for fuel production is the same sub-processes as AD1 for electricity production, except for combustion at the CHP plant (see Figure 4). The exploitation of biogas for fuel usage required improving the gas to remove CO_2, water, and Sulphur and to end up with a methane content of P95% [17].

Scenario 5: Fermentation for bioethanol

During the initial fermentation process, the municipal solid waste (MSW) is shredded. Next, a mixture of the shredded MSW and water undergoes continuous weak acid hydrolysis under high pressure (62 bar) and high temperature (between 260 and 280 °C). This process converts the cellulosic material into sugar. Following this, a fermentation operation converts the sugar into dilute ethanol, which is then purified through a distillation process to produce bioethanol for use as fuel (see Figure 5) [18-19].

Table 1: The conversion technology-based scenarios

Scenario Label	Scenario Name	Produced Bioenergy
Scenario 1	Pyrolysis for electricity	Bioelectricity
Scenario 2	Anaerobic digestion for heat and electricity (AD1)	Bioelectricity
Scenario 3	Anaerobic digestion for household gas (AD2)	Household biogas
Scenario 4	Anaerobic digestion for fuel gas (AD3)	Fuel biogas
Scenario 5	Fermentation for bioethanol	Bioethanol
Scenario 6	Landfill gas collection for household use	Household biogas

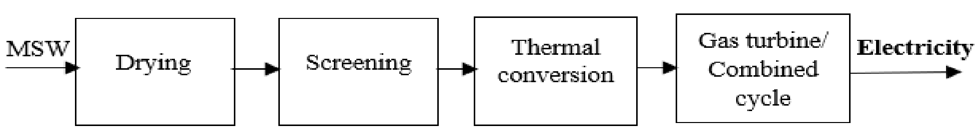

Figure 1: The system boundary for the pyrolysis system

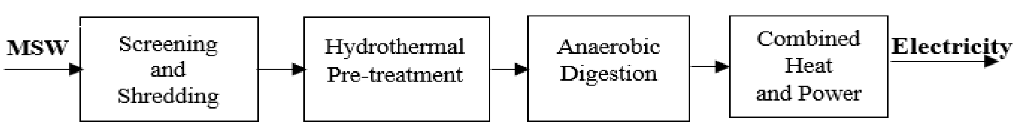

Figure 2: The system boundary of the anaerobic digestion system for electricity production

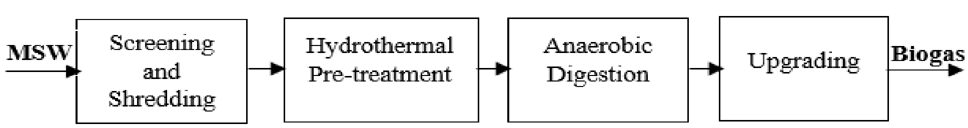

Figure 3: The system boundary of the anaerobic digestion system for household gas production

Scenario 6: Landfill gas collection for household use

In this scenario, MSW is collected in sanitary landfills with the recovery of biogas, and the leachate is removed. The life cycle of the Landfill system for gas collection is designed based on the process suggested by Doka (2009). Concerning this method and the MSW composition, the landfill system could produce 1102 MJ of biogas per ton of MSW. Figure 6 shows the life cycle of this scenario [20].

Life cycle economic assessment

The economic assessment of the life cycle is possible using various financial indicators, including total life cycle expense, total life cycle benefit, Net present value (NPV), Benefit to cost(B/C), Internal rate of return (IRR), Payback period (PBP), *etc.* [4,12]. This study considered the total life cycle expense, total life cycle benefit, NPV, and B/C of each scenario based on the stakeholder's decision, and a comparison of six scenarios was conducted based on the chosen financial indicators.

Primary assumptions

The primary assumption for conducting a life cycle economic assessment was based on the technical life cycle assessment of converting MSW to bio-energies, as detailed in Tables 2 and 3.

Notation

The list of sets, parameters, and variables in the financial mathematical model for bio-energies generation is according to Tables 4 to 6.

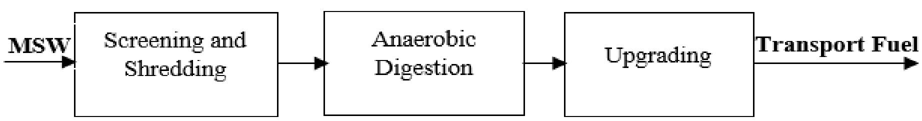

Figure 4: The system boundary of the anaerobic digestion system for fuel gas production

Figure 5: The system boundary of the fermentation system

Figure 6: The system boundary of the Landfill gas collection system

Table 2: The main assumption for life cycle economic assessment

Parameter	Unit	Value
Project lifetime	Years	10
The percentage of blending bioethanol with gasoline	E5	Including 5% anhydrous bioethanol and 95% gasoline*
Rate of interest	% Per annum	25

**Based on feasibility studies.*

Table 3: The technology efficiencies

Technologies	Bioenergy	Unit	Efficiency
Pyrolysis	Electricity	kWh/t*	685
Anaerobic digester	Electricity	kWh/t	93.37
	Biogas household	M^3/t	76.36
	Biogas fuel	M^3/t	42.78
Fermentation	Bioethanol	L/t	87.69
Landfill with gas	Biogas	M^3/t	30.2

**Ton of MSW.*

Table 4: The list of Sets for the suggested model

Sets	Description
S	Set of nodes for MSW collection zones {s = 1,……., S}
I	Set of nodes for generation site {i = 1,……., I}
J	Set of nodes for customer zones {j = 1,……., J}
BE	Set of bio-energies /bioelectricity, bioethanol, biogas for domestic use, biogas for fuel/ {be =1, ……., BE}
W	Set of all types of MSW {w = 1,……., W}
TE	Set of treatment technologies /Anaerobic digestion for heat and electricity, Anaerobic digestion for household gas, Anaerobic digestion for fuel gas, Pyrolysis, Fermentation, Landfill gas collection/{te =1,……., TE}
T	Set of planning periods {t =1,……., T}

Table 5: The list of parameters

Parameters	Description
$WT_{t\ te}$	The amount of MSW w that is entered into the site i in a period of t (ton) and assigned to the facility with technology te
$CA_{te\ t}$	Maximum capacity(ton) of the facility with technology te at time t for processing MSW w
$ca_{te\ t}$	Capacity(ton) of the facility with technology te at time t for processing MSW w
$S_{be\ t}$	The selling price (USD) of bioenergy units in the period time of t
Cf_t	The annual cash flow
C_0	The initial investment cost
$CP_{te\ t}$	Operating cost (USD/ton) of the facility with technology te at time t
$CC_{te\ t}$	The capital cost (USD) of establishing a facility with technology te in a period of t
$C_{be\ t}$	Unit transportation cost per kilometer for transferring unit of bioenergy be generated in period t (USD.km^{-1}/bioenergy unit)
C_{si}	Unit transportation cost per kilometer for transferring units of MSW collected in period t (USD.km^{-1}/ton)
$EF_{te\ be}$	The efficiency of equipment with te technology for bioenergy production be by processing MSW /bioelectricity(kWh.ton^{-1}), bioethanol (L.ton^{-1}), biogas for domestic use (M^3.ton^{-1}), biogas for fuel (M^3.ton^{-1})/
dis_{ij}	The distance (km) between generation site i and customer zone j
$dis_{s\ i}$	The distance (km) between collection zone s and generation site i
r	The interest rate
n	The lifetime of the investment

Table 6: The list of variables

Variables	Description
$PD_{be\ te\ t}$	The amount of bioenergy *be*/bioelectricity(kWh), bioethanol(L), biogas for domestic use(M^3), biogas for fuel(M^3) / produced by the facility with technology *te* in period *t*

Total bioenergy life cycle benefit

The income of this research is gained from the commercialization of bio-energies. These bio-energies included bioelectricity, biogas for households, biogas fuel, and bioethanol fuel. The following Equations (1) to (4) calculate the profit from the commercialization of bio-energies in each scenario, the capacity of each piece of equipment with technology *te*, and the amount of bio-energies production respectively:

$$B(BE,TE) = \sum_t (1+r)^{-(t-1)} S_{be\ t} PD_{be\ te\ t}$$

$$\forall te \in TE\ , be \in BE \qquad (1)$$

$$CA_{tet} = WT_{t\ te} \qquad t = T\ ,\ \forall te \in TE \qquad (2)$$

$$ca_{te\ t} = CA_{tet} \qquad \forall\ t \in T, te \in TE \qquad (3)$$

$$PD_{be\ te\ t} = EF_{te\ be}\ WT_{te\ t}$$

$$\forall t \in T\ , te \in TE\ , be \in BE \qquad (4)$$

Equation (2) depicts the relation between the maximum capacity of equipment and the amount of MSW allocated to each facility. Equation (3) also indicates that the capacity of each equipment with *te* technology is supposed to be equal to its maximum capacity.

Total bioenergy life cycle cost

Equation (5) calculates the total bioenergy life cycle cost. The first term is related to the present value of investment cost for establishing the facility of treatment technologies. The second is about the present value of the operation cost of these facilities. The third term is associated with the expense of shipping generated bio-energies from the facilities of treatment technologies to customers. The fourth term indicates the expenditure on transporting gathered MSW from the collector stations to the treatment site.

$$C(BE,TE) = \sum_t \sum_{te} CC_{te\ t}\,(1+r)^{-(t-1)} +$$

$$\sum_t \sum_{te} CP_{te\ t}\, WT_{te\ t} (1+r)^{-(t-1)} +$$

$$\sum_i \sum_j \sum_t C_{be\ t} dis_{ij} PD_{be\ te\ t} (1+r)^{-(t-1)} +$$

$$\sum_s \sum_i \sum_t C_{si} dis_{si} WT_{te\ \ t} (1+r)^{-(t-1)}$$

$$\forall te \in TE\ , be \in BE \qquad (5)$$

Net Present Value (NPV)

Net present value (NPV) is a key financial indicator used to evaluate the profitability of a project, which is the sum of the annual cash flows. The following formula is applied to calculate the NPV:

$$NPV = -C_0 + \sum_{t=1}^{n} \frac{Cf_t}{(1+r)^t} \qquad (6)$$

Where NPV is the net present value, C0 is the initial investment cost, Cf t is the annual cash flow, being the difference between cash inflows and cash outflows, r is the annual discount rate taken as 25%; and n is the lifetime of the project. Cash inflows are profits earned from bio-energies sales and other benefits, including incentives, tax forgiveness, subsidies, etc. Cash outflows also include the cost of investment, operation, moving waste, bio-energies, etc. A positive NPV indicates the economic feasibility of the selected technology, and the expanded equation 6, based on the total bioenergy life cycle benefit (Equation 1) and total bioenergy life cycle cost (Equation 5), is as follows [4,21]:

$$NPV(BE,TE) = \sum_t (1+r)^{-(t-1)} S_{be\,t} PD_{be\,te\,t} - \sum_t CC_{tet}(1+r)^{-(t-1)} - \sum_t CP_{tet} WT_{tet}(1+r)^{-(t-1)} - \sum_i \sum_j \sum_t C_{bet} dis_{ij} PD_{betet}(1+r)^{-(t+1)} - \sum_s \sum_i \sum_t C_{si} dis_{si} WT_{te\,t}(1+r)^{-(t-1)}$$

$$\forall te \in TE\,,\, be \in BE \qquad (7)$$

The first term is about the cash inflow of this research based on selling the bio-energies. The second term to the fifth is related to cash outflows of this research based on the present value of total expenditures to generate bio-energies.

Benefit to Cost Ratio (BCR)

The other financial indicator is the benefit-cost ratio (BCR), which depicts the relationship between the relative costs and benefits of the proposed investment in this research (see Equation (8)). To calculate this ratio, it is estimated the present value of all benefits and costs generated by scenario establishing.

$$BC(BE,TE) = \frac{B(BE,TE)}{C(BE,TE)}$$

$$\forall\, te \in TE, be \in BE \qquad (8)$$

Equation (1) indicates the present value of all benefits, and Equation (5) calculates the cost of production and commercialization of bio-energies.

Case study description

In this study, Aradkoh, located in the south of Tehran, which has been receiving MSW from 11 distribution centers since 1976, was selected as a case study. The approximate area of this center is about 1400 hectares, and a daily average of 7400 tons of MSW are imported to this center. These wastes are collected from the 22 districts of Tehran, including daily household waste, hospital waste, company waste, and others. The preliminary step is to weigh MSW. Thereafter, some wastes are delivered to the process and reuse centers for MSW processing, and compost making, etc. are transferred to the landfill [22-23].

Economic assessment comparison results and discussion

The capital investment of different scenarios, including pyrolysis, AD1, AD2, AD3, fermentation, and landfill gas collection, for about 5000 tons per day, was estimated. The values of this capital cost were about $949.91 million, $315.17 million, $315.17 million, $315.17 million, $766.42 million, and $31.52 million respectively(see Table 7).

The operating cost of six scenarios was calculated based on the daily input capacity of MSW, which is about 5,000 tons. These costs included the expenditures by labor costs, facility maintenance, utility, etc. The calculated operation costs in the first year were about $103.55 million, $28.62 million, $28.62 million, $28.62 million, $256.13 million, and $2.86 million, respectively(see Table 8). The principal earned income in different scenarios is based on the sale of generated bio-energies, including bioelectricity, biogas for home use, biogas fuel, and bioethanol fuel, during a lifetime. These revenues in the first year were about $180.05 million, $22.05 million, $26.44 million, $18.37 million, $164.63 million, and $10.46 million, respectively.

Comparison in terms of NPV

In this study, we employed the NPV to assess the profitability of various scenarios. Table 9 presents the calculated NPVs for six distinct scenarios, using an interest rate of 25% per annum. The estimated NPVs suggest that implementing landfill gas technology represents a viable option among conversion technologies. The ranking of the other technologies follows with anaerobic digestion (AD2, AD1, and AD3), pyrolysis, and fermentation, respectively.

Comparison in terms of benefit to cost

To assess the ratio, the present value of all benefits and costs associated with each scenario was analyzed. The findings from this analysis are summarized in Table 10, which ranks landfill gas as the top option, followed by pyrolysis in second place. The technologies of fermentation, AD2, AD1, and AD3 follow in that order. The favorable benefit-cost ratio clearly indicates a strong potential return on investment for the landfill gas scenario compared to the other scenarios examined in this study.

Table 7: The results of capital cost calculation of six scenarios

Conversion Technologies	Pyrolysis	AD1	AD2	AD3	Fermentation	Landfill-gas
Capital cost (million$)	949.91	315.17	315.17	315.17	766.42	31.52

Table 8: The results of operation costs calculation of six scenarios in the first year

Conversion Technologies	Pyrolysis	AD1	AD2	AD3	Fermentation	Landfill-gas
Operation costs(million$)	103.55	28.62	28.62	28.62	256.13	2.86

Table 9: The results of NPV calculation of six scenarios

Conversion Technologies	Pyrolysis	AD1	AD2	AD3	Fermentation	Landfill-gas
NPV (million$)	-582.92	-347.33	-325.55	-364.83	-1,209	5.28
Rank	5	3	2	4	6	1

Table 10: The results of the B/C calculation of six scenarios

Conversion Technologies	Pyrolysis	AD1	AD2	AD3	Fermentation	Landfill-gas
B/C	0.6	0.23	0.28	0.2	0.4	1.12
Rank	2	5	4	6	3	1

Sensitivity analysis

In this research, policymakers chose not to impose a budget limit, which allowed us to prioritize the NPV as the main financial indicator. To analyze how various input parameters affect the NPV, we investigated the effects of ± 25% changes in these parameters from their baseline values across all scenarios. This approach assists decision-makers in identifying strategies to maximize the project's benefits. The selling prices of bioelectricity, biogas, biogas fuel, and biofuel were changed by ±25%. Additionally, other input parameters, including efficiency, capital cost, operational cost, and input MSW, were varied by ± 25%. In all six scenarios, the parameters that adversely impacted NPV were the capital cost and operational cost. Furthermore, the MSW parameter had a negative impact on the NPV in five of the scenarios, with the exception of the scenario involving a landfill with gas technology. The key parameters that positively contributed to enhancing the NPV were efficiency and the selling prices of bio-energies. In the scenario of landfill gas technology, the most effective parameters were efficiency and selling price. A 25% increase in both the efficiency and the selling price of biogas can lead to a remarkable 240% increase in the current NPV of the landfill gas project. In contrast, capital costs negatively impact the NPV; reducing these costs by 25% can result in a 149% increase in NPV. In the fermentation scenario, two critical parameters, operating costs and MSW, had a negative effect. A decrease in operating costs of up to 25% could result in an increase of approximately

26% in the NPV of this scenario. Similarly, an increase in the volume of MSW by up to 25% could lead to a growth of 25% in the current NPV of this scenario. The next most important influencing parameters on this scenario were efficiency, biofuel sales price, and capital costs, respectively. The main factors influencing the pyrolysis scenario were the capital cost, the selling price of bioelectricity, and the efficiency of the system. A 25% change in both the selling price and the system's efficiency can result in an equivalent increase in the NPV of 37%. In contrast, a 25% increase in capital costs can result in a decrease of 41% in the NPV. In all three scenarios, including AD1, AD2, and AD3, the input value of MSW was the most influential factor affecting the NPV. There was an inverse relationship between MSW and NPV. Specifically, when the MSW input changed by ±25%, the NPV fluctuated in the opposite direction. This resulted in a 25% increase or decrease in NPV for generating bioelectricity, biogas for home use, and biogas fuel. In scenario AD1, several factors affected the NPV in addition to MSW. These factors included capital costs, operational costs, efficiency, and the electricity selling price. There was an inverse relationship between capital costs and operational costs concerning NPV. When capital costs changed by ±25%, the NPV varied inversely by approximately ±23%. Similarly, when operational costs changed by ±25%, the NPV shifted inversely by about ±10%. Furthermore, increasing both efficiency and the selling price by 25% could lead to an approximate 8% increase in NPV. In scenario AD2, several critical factors negatively impacted the NPV. Specifically, a 25% increase in both capital and operating costs resulted in a decline of 24% and 11% in NPV for biogas production, respectively. Additionally, the efficiency and selling price of biogas were evaluated; a 25% increase in both these factors led to an approximate 10% rise in NPV. According to the analysis of scenario AD3, similar to the previous two scenarios, the key parameters that negatively affected the NPV were capital and operating costs. A 25% reduction in both capital and operating costs resulted in approximately a 22% and 9% increase, respectively, in NPV for biogas fuel production using AD3.

Moreover, the following factors of efficiency and selling price had an equal effect on NPV. Increasing both parameters by up to 25% can result in a 6% rise in NPV(see Figure 7).

Conclusion

This study conducted a comparative techno-economic assessment of the life cycles for six distinct scenarios to identify the most effective MSW treatment technologies for producing different forms of bio-energies. These energies included electricity, biogas for household use, biogas as a fuel, and bioethanol. The life cycle analysis of collecting landfill gas for household use showed a positive NPV of $5.28 million across the six scenarios evaluated.

In contrast, the other scenarios generated negative NPV outcomes. The NPVs for each option were as follows: -$347.33 million for anaerobic digestion for household gas, -$325.55 million for anaerobic digestion for heat and electricity, -$364.83 million for anaerobic digestion for fuel gas, -$582.92 million for pyrolysis, and -$1,209 million for fermentation. The sensitivity analysis indicated that producing bioenergy and biofuels with high efficiency can greatly enhance the NPV. Therefore, it is highly recommended that stakeholders allocate an adequate budget for research and development (R&D) to advance the readiness of conversion technologies.

To equalize the costs of establishing conversion technologies, the government should encourage venture capital to invest in treatment technologies that produce bioenergy by providing financial and technical incentives, such as subsidies, tax exemptions, and technical support.

Since the NPV for bioenergy production across the five scenarios is negative, and given that these bioenergy alternatives aim to replace non-renewable energy sources, it is advisable to conduct a comparative economic assessment in the future. This assessment should evaluate energy production derived from MSW in comparison to non-renewable sources. Relying solely on the economic assessment of LC is not enough when making sustainable decisions.

Furthermore, it is essential to conduct social and environmental assessments. The results of these assessments should be combined with the economic findings to develop a comprehensive sustainable model for converting MSW into bio-energies.

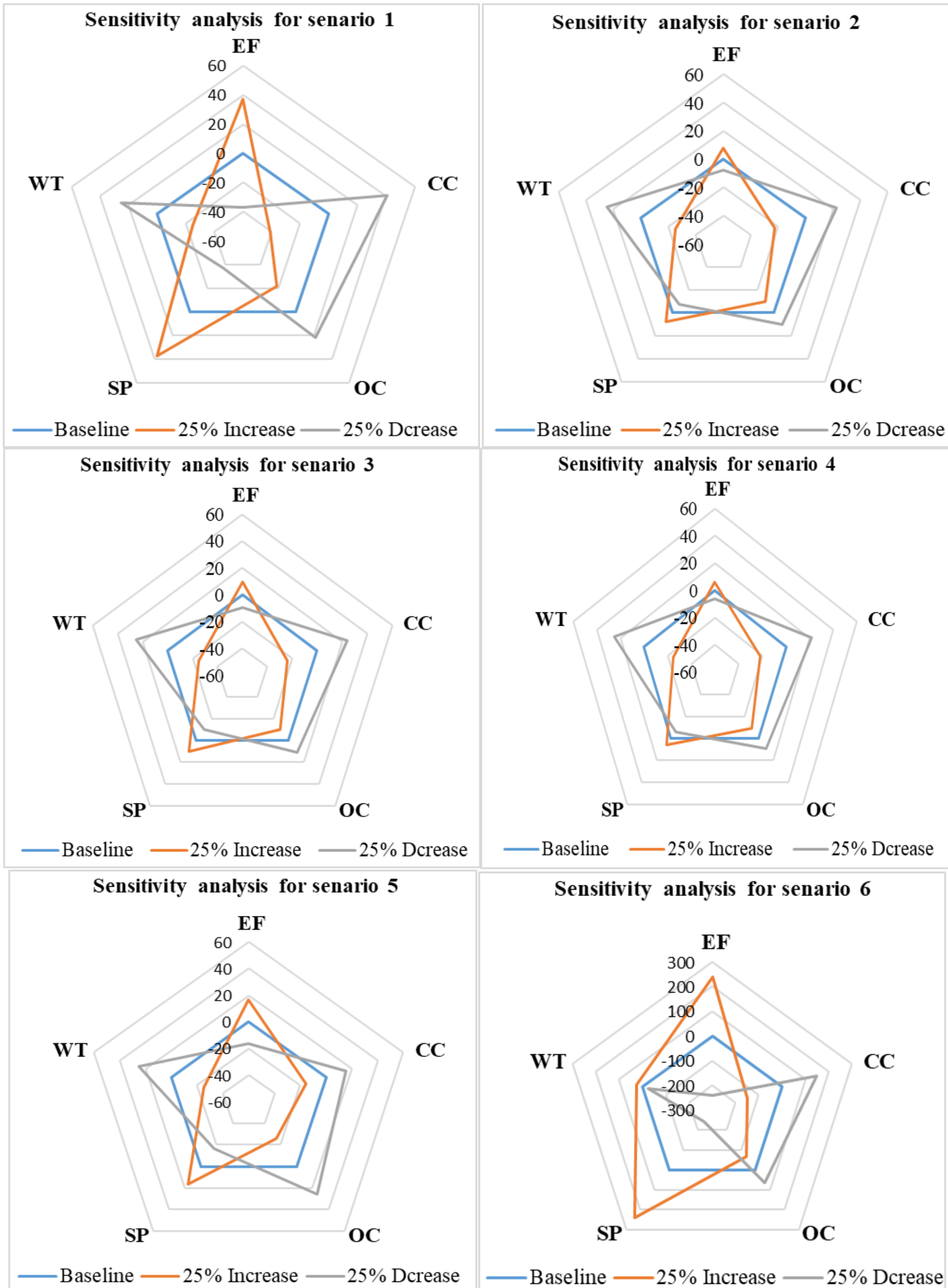

Figure 7: The separate results of the sensitivity analysis for the NPV in scenarios 1 to 6

Acknowledgments

The authors would like to express our sincere thanks to the unnamed reviewers for their precious and advantageous viewpoints.

Conflict of Interest

No conflict of interest was declared by the authors in this work.

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Reference

[1] F.C. Luz, M.H. Rocha, E.E.S. Lora, O.J. Venturini, R.V. Andrade, M.M.V. Leme, O.A. del Olmo, Techno-economic analysis of municipal solid waste gasification for electricity generation in Brazil, *Energy Conversion and Management*, **2015**, *103*, 321-337. [Crossref], [Google Scholar], [Publisher]

[2] C.A. Salman, S. Schwede, E. Thorin, J. Yan, Enhancing biomethane production by integrating pyrolysis and anaerobic digestion processes, *Applied Energy*, **2017**, *204*, 1074-1083. [Crossref], [Google Scholar], [Publisher]

[3] Y. Yang, J. Wang, K. Chong, A.V. Bridgwater, A techno-economic analysis of energy recovery from organic fraction of municipal solid waste (MSW) by an integrated intermediate pyrolysis and combined heat and power (CHP) plant, *Energy Conversion and Management*, **2018**, *174*, 406-416. [Crossref], [Google Scholar], [Publisher]

[4] T. Ayodele, A. Ogunjuyigbe, M. Alao, Economic and environmental assessment of electricity generation using biogas from organic fraction of municipal solid waste for the city of Ibadan, Nigeria, *Journal of Cleaner Production*, **2018**, *203*, 718-735. [Crossref], [Google Scholar], [Publisher]

[5] S. Afrane, J.D. Ampah, C. Jin, H. Liu, E.M. Aboagye, Techno-economic feasibility of waste-to-energy technologies for investment in Ghana: A multicriteria assessment based on fuzzy TOPSIS approach, *Journal of Cleaner Production*, **2021**, *318*, 128515. [Crossref], [Google Scholar], [Publisher]

[6] H. Nassar, M. Biltagy, A.M. Safwat, The role of waste-to-energy in waste management in Egypt: A techno-economic analysis, *Review of Economics and Political Science*, **2025**, *10*, 151-167. [Crossref], [Google Scholar], [Publisher]

[7]. M.S. Khan, J. Cui, Y. Ni, M. Yan, M. Ali, Techno-economic and Exergo-Economic evaluation of a novel solar integrated waste-to-energy power plant, *Applied Thermal Engineering*, **2023**, *223*, 119929. [Crossref], [Google Scholar], [Publisher]

[8] M.-J. Park, S. Yun, D.-W. Jeong, W. Won, Upcycling municipal solid waste: Scenario-based techno-economic evaluation and life cycle assessment, *Energy*, **2025**, 136786. [Crossref], [Google Scholar], [Publisher]

[9] M. Van de Velden, J. Baeyens, A. Brems, B. Janssens, R. Dewil, Fundamentals, kinetics and endothermicity of the biomass pyrolysis reaction, *Renewable energy*, **2010**, *35*, 232-242. [Crossref], [Google Scholar], [Publisher]

[10] J. Dong, Y. Tang, A. Nzihou, Y. Chi, E. Weiss-Hortala, M. Ni, Life cycle assessment of pyrolysis, gasification and incineration waste-to-energy technologies: Theoretical analysis and case study of commercial plants, *Science of the Total Environment*, **2018**, *626*, 744-753. [Crossref], [Google Scholar], [Publisher]

[11] D. Chen, L. Yin, H. Wang, P. He, Pyrolysis technologies for municipal solid waste: a review, *Waste Management*, **2014**, *34*, 2466-2486. [Crossref], [Google Scholar], [Publisher]

[12] M.M.-U.-H. Khan, S. Jain, M. Vaezi, A. Kumar, Development of a decision model for the techno-economic assessment of municipal solid waste utilization pathways, *Waste Management*, **2016**, *48*, 548-564. [Crossref], [Google Scholar], [Publisher]

[13] F. Demichelis, T. Tommasi, F. Deorsola, D. Marchisio, G. Mancini, D. Fino, Life cycle assessment and life cycle costing of advanced anaerobic digestion of organic fraction municipal solid waste, *Chemosphere*, **2022**, *289*, 133058. [Crossref], [Google Scholar], [Publisher]

[14] H. Xiao, D. Zhang, Z. Tang, K. Li, H. Guo, X. Niu, L. Yi, Comparative environmental and economic life cycle assessment of dry and wet anaerobic digestion for treating food waste and biogas digestate, *Journal of Cleaner Production*,

2022, *338*, 130674. [Crossref], [Google Scholar], [Publisher]
[15] S. Belboom, J.M. Digneffe, R. Renzoni, A. Germain, A. Léonard, Comparing technologies for municipal solid waste management using life cycle assessment methodology: a Belgian case study, *The International Journal of Life Cycle Assessment*, **2013**, *18*, 1513-1523. [Crossref], [Google Scholar], [Publisher]
[16] C. Beausang, K. McDonnell, F. Murphy, Anaerobic digestion of poultry litter–a consequential life cycle assessment, *Science of the Total Environment*, **2020**, *735*, 139494. [Crossref], [Google Scholar], [Publisher]
[17] T. Fruergaard, T. Astrup, Optimal utilization of waste-to-energy in an LCA perspective, *Waste Management*, **2011**, *31*, 572-582. [Crossref], [Google Scholar], [Publisher]
[18] M.A. Bozorgirad, H. Zhang, K.R. Haapala, G.S. Murthy, Environmental impact and cost assessment of incineration and ethanol production as municipal solid waste management strategies, *The International Journal of Life Cycle Assessment*, **2013**, *18*, 1502-1512. [Crossref], [Google Scholar], [Publisher]
[19] M.G. Chacón, C. Ibenegbu, D.J. Leak, Simultaneous saccharification and lactic acid fermentation of the cellulosic fraction of municipal solid waste using Bacillus smithii, *Biotechnology Letters*, **2021**, *43*, 667-675. [Crossref], [Google Scholar], [Publisher]
[20] H.K. Jeswani, A. Azapagic, Assessing the environmental sustainability of energy recovery from municipal solid waste in the UK, *Waste Manag*, **2016**, *50*, e63. [Crossref], [Google Scholar], [Publisher]
[21] Z. Alidoosti, A. Sadegheih, K. Govindan, M.S. Pishvaee, Sustainable network design of bioenergies generation based on municipal solid waste (MSW) management under uncertainty, *Journal of Renewable and Sustainable Energy*, **2023**, *15*. [Crossref], [Google Scholar], [Publisher]
[22] A.M. Harijani, S. Mansour, B. Karimi, C.-G. Lee, Multi-period sustainable and integrated recycling network for municipal solid waste–A case study in Tehran, *Journal of Cleaner Production*, **2017**, *151*, 96-108. [Crossref], [Google Scholar], [Publisher]