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Biogas for Sustainability: Waste-to-Energy Conversion and Environmental Benefits

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Abstract

This study evaluates the Batman Solid Waste Management Project from the perspective of sustainable energy production and benefit-cost analysis. Utilizing the 2009-2010 Final Environmental Impact Assessment (EIA) Report, TÜİK (Turkish Statistical Institute) population projections, waste characterization-based market data, and environmental and socio-economic indicators, the project's direct and indirect economic and environmental impacts are analyzed. Serving a population increasing from 387,230 in 2012 to 508,648 by 2030, the project aims to reduce environmental pollution, enhance recycling rates, and support socio-economic development. Economic benefits are projected at €1.5–9.7 million in the first operational year and €2.1–13.3 million by 2030. Biogas production rises from 6.29 million m³ in 2009 to 13.98 million m³ by 2030, with electricity generation increasing from 7.86 million kWh to 17.47 million kWh. Environmental benefits include a 221,855 ton CO_2e emission reduction by 2030, predominantly due to methane capture (94–95% contribution). However, the wide range of benefits reflects economic uncertainties, necessitating transparent calculations and sensitivity analyses. The project's success depends on managing environmental risks, securing local community acceptance, and aligning with national energy policies. It holds significant potential to contribute to Turkey's alignment with the EU (European Union) environmental acquis and renewable energy targets.

Keywords: Biogas, Environmental Benefit Analysis, Energy Production, Greenhouse Gas Emissions, Sustainability

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INTRODUCTION

Sustainable development requires innovative solutions that balance environmental, economic, and social dimensions on a global scale. In this context, solid waste management plays a critical role in reducing environmental pollution and harnessing renewable energy potential to achieve sustainability goals. Biogas production, through the anaerobic fermentation of organic waste, captures methane gas, contributing to energy production while mitigating uncontrolled methane emissions, thus serving as an effective tool in combating climate change (IPCC, 2021; Scarlat et al., 2018). Bioenergy, particularly biogas, holds strategic importance in enhancing energy supply security and reducing fossil fuel dependency in developing countries (IEA, 2023). As the importance of biogas in the global energy transition grows, this technology offers multifaceted benefits by integrating waste management and renewable energy production. In developing countries, rising waste volumes due to population growth and urbanization make biogas facilities increasingly attractive from both environmental and economic perspectives (IEA, 2022).

Turkey, facing increasing waste management demands due to rapid urbanization and industrialization, is adopting innovative waste management projects to align with the EU environmental acquis. The Batman Solid Waste Management Project, located in southeastern Turkey, provides a case study for evaluating the integration of sustainable waste management and biogas production. Analyzed using the 2009-2010 Final EIA Report, TÜİK population projections, waste characterization-based market data, and environmental and socio-economic indicators, the project targets a population growing from 387,230 in 2012 to 508,648 by 2030. It aims to reduce environmental pollution, increase recycling rates, and foster socio-economic development. This study assesses the project's direct and indirect economic, environmental, and social impacts within a benefit-cost analysis framework, highlighting biogas's role in sustainable energy production and regional development. The literature underscores the potential of biogas projects to reduce methane emissions and enhance energy supply security (Scarlat et al., 2018; IEA, 2022). The Batman project exemplifies Turkey's renewable energy goals and alignment with EU environmental standards. Biogas facilities contribute significantly to Europe's sustainability objectives by producing energy from organic waste and controlling methane emissions (Capodaglio & Callegari, 2022). Additionally, this study examines the critical role of factors such as local community acceptance, economic uncertainty management, and technological innovation integration in the project's success, offering actionable insights for policymakers and stakeholders (Tumur, 2025).

Designed to serve a population expanding from 387,230 in 2012 to 508,648 in 2030, the project aims to mitigate environmental pollution, enhance recycling efficiency, and foster socio-economic progress. The anticipated economic benefits amount to €1.5–9.7 million during the first operational year, increasing to €2.1–13.3 million by 2030. Biogas output is projected to rise from 6.29 million m³ in 2009 to 13.98 million m³ by 2030, accompanied by an increase in electricity generation from 7.86 million kWh to 17.47 million kWh. Environmental advantages include a reduction of 221,855 tons of CO_2e emissions by 2030, primarily driven by methane capture, which accounts for 94–95% of the total mitigation.

In Turkey, biogas production reduces environmental pollution and enhances regional energy supply security by valorizing organic waste within a circular economy framework (Akyürek & Çetinkaya, 2023).

Study Area

The project is located in Batman Province, within Turkey's Southeastern Anatolia Region, positioned between 41°10'–41°40' E longitude and 37°50'–38°40' N latitude. The province has an elevation of 550 meters above sea level and is bordered by Bitlis and Siirt to the east, Muş to the north, Diyarbakır to the west, and Mardin to the south. Batman's central district is 218 km from Muş, 149 km from Mardin, 135 km from Bitlis, 100 km from Diyarbakır, and 87 km from Siirt. The province covers a total area of 4,654 km². The location of Batman Province within Turkey is shown in Figure 1, and a map of Batman Province and its districts is provided in Figure 2 (General Directorate of Mapping, 2024).

Figure 1. Location of Batman Province in Turkey

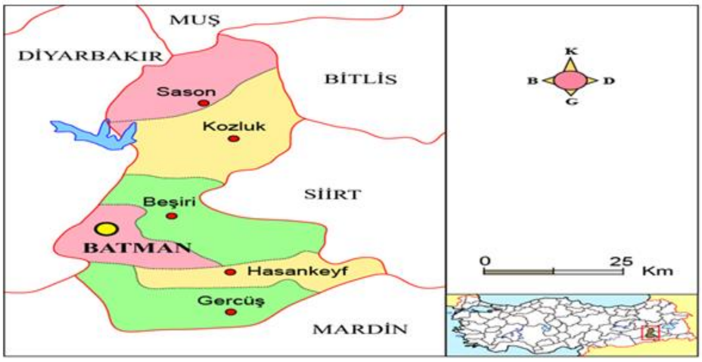

Figure 2. Map of Batman Province and Its Districts.

Facility overview

The Batman Solid Waste Facility is located on parcel no. 371 in Binatlı Village, Batman Central District, covering approximately 400,864.53 m². The nearest settlements are Yolveren Village (2 km southeast) and Kolbaşı Village (2 km northwest). The project site is 6 km from the nearest fuel station, 17 km from the nearest industrial zone, and 17 km from the airport.

Under the Batman Solid Waste Facilities Implementation and Operation Union (BKABB), established by a Council of Ministers decision on November 1, 2008 (2008/14230), the facility processes waste from Batman Central Municipality, Beşiri Municipality, and anticipated members, including Balpınar, İkiköprü, Hasankeyf**,** Gercüş, Kozluk, Sason, and Bekirhan municipalities, as well as six villages in Batman's districts. Distances from municipalities and villages to the project site are presented in Table 1.

Table 1. Distances of Municipalities and Villages to the Project Site

Municipality	Distance to Project Site (km)	Village	Distance to Project Site (km, straight line)
Batman	17	Aydınkonak	13
Beşiri	29	Akça	8
Hasankeyf	31	Demiryol	15
Gercüş	54	Erköklü	11
Kozluk	79	İkiztepe	17.5
Sason	85	Binatlı	5.2
Balpınar	26		
İkiköprü	34		
Bekirhan	55		

MATERIALS AND METHODS

Data sources

This study evaluates the Batman Solid Waste Management Project using a combination of official reports and regional data. The primary sources include the 2009–2010 Final Environmental Impact Assessment (EIA) Report, population projections from the Turkish Statistical Institute (TÜİK), and waste characterization studies conducted by Batman Municipality. In addition, regional electricity prices, recycling market data, and socio-economic indicators were used to estimate both economic and environmental outcomes.

Study scope

The analysis covers Batman Province and the surrounding municipalities served by the facility. The time frame corresponds to the project's economic life (2012–2030). The assessment focuses on three main dimensions:

Economic impacts (direct revenues, costs, and job creation)

Environmental impacts (greenhouse gas reduction, pollution prevention)

Social impacts (public health, acceptance, and community benefits)

Facility overview

The Batman Solid Waste Management Facility is located in Binatlı Village, approximately 17 km from Batman city center. The project was initiated by the Batman Solid Waste Facilities Implementation and Operation Union (BKABB) with the aim of providing an integrated waste management solution for the central district and nearby municipalities.

The facility combines several complementary systems:

Sanitary landfill: Engineered to minimize environmental risks, with impermeable liners, leachate drainage, and methane collection systems.

Biogas recovery and utilization system: Methane gas is extracted through vertical wells and conveyed to gas engines, where it is converted into electricity and heat.

Composting and recycling units: Designed to treat the organic fraction of waste and recover materials such as paper, glass, plastics, and metals. Processes 2,500 tons of organic waste annually, handling 7 tons of waste (23.3 m^3) and 0.5 tons of coarse material (3.3 m^3) daily (Table 2). Composting takes 3 months, with a 2-month maturation period, assuming a 50% volume reduction and 10% non-acceptable waste (Table 3).

Auxiliary infrastructure: Includes wastewater treatment, administrative buildings, and monitoring stations.

These components were considered collectively in the analysis, with emphasis placed on their contribution to renewable energy generation and the reduction of environmental pressures.

Figure 3. General Layout of Facility Units

Table 2. Inputs of the Composting Facility

Quantity	Ton	Volume
Waste	7 t/day	23.3 m³/day
Coarse Material	0.5 t/day	3.3 m³/day
Total Quantity	7.5 t/day	26.6 m³/day

Table 3. Composting Facility Assumptions

Parameter	Value
Waste Density	300 kg/m³
Coarse Material Density	150 kg/m³
Compost Density	600 kg/m³
Composting Duration	3 months
Maturation Duration	2 months
Volume Reduction	50%
Non-Acceptable Waste	10%
Pile Dimensions	Base 6 m, top 1 m, height 2.5 m

Waste data and projections

Waste generation estimates were based on TÜİK's population projections and local waste characterization surveys. In 2015, approximately half of municipal waste consisted of biodegradable materials (mainly food and garden waste), making it suitable for biogas production. Total waste volumes were projected to rise from about 100,000 tons in 2009 to over 220,000 tons by 2030, in line with regional population growth. These figures formed the basis for calculating future energy potential and environmental benefits.

Waste characterization

Accurate waste characterization formed the foundation of this study. According to municipal surveys, nearly 50% of Batman's municipal solid waste consists of organic matter, predominantly food residues and garden waste. The remainder is distributed among recyclable fractions (plastics, paper, metals, glass) and inert material.

Population growth exerts a significant influence on waste generation. TÜİK data indicate that Batman's population will rise from 387,230 in 2012 to 508,648 by 2030. Assuming constant per capita waste generation, total annual waste is expected to increase from 100,634 tons in 2009 to 223,601 tons in 2030. These values served as the input for calculations of biogas and electricity potential.

The study also considered seasonal variations in waste composition, though the annual averages were used for benefit–cost analysis to provide a consistent basis for projections.

Table 4. Waste Characterization

Material	**Average (%)**
Food Waste	38.7
Paper	3.3
Cardboard	2.2
Bulky Cardboard	4.7
Plastic	12.3
Glass	2.1
Metal	2.1
Bulky Metal	0.0
Waste Electrical/Electronic Equipment	0.1
Hazardous Waste	0.8
Park and Garden Waste	11.9
Other Non-Combustible Materials	6.6
Other Combustible Materials	0.0
Other Combustible Bulky Waste	0.8
Other Non-Combustible Bulky Waste	11.8
Other	3.4
Total	100

Biogas and energy conversion assumptions

To estimate energy production, standard conversion factors were applied:

1 ton of organic waste generates approximately 125 m³ of biogas.

1 m³ of biogas yields around 1.25 kWh of electricity.

The facility operates for an average of 8,000 hours annually.

These values were applied to projected waste quantities to calculate annual energy outputs for the period 2009–2030.

Analytical framework

The assessment employed a Benefit–Cost Analysis (BCA) to determine whether the project generates net positive value across its operational lifetime. The framework included three main dimensions:

Economic dimension: Revenues from electricity generation, recyclable material sales, and compost/biofertilizer production. Avoided costs from unregulated landfilling (land occupation, remediation, uncontrolled methane release) were also considered.

Environmental dimension: Reduction in greenhouse gas emissions due to controlled methane capture and renewable electricity generation. Additional benefits included reduced soil and water contamination and decreased reliance on fossil fuels.

Social dimension: Health improvements linked to reduced exposure to uncontrolled waste, job creation, and contributions to regional socio-economic development.

Monetary values were assigned to measurable benefits, while qualitative impacts (e.g., improved community acceptance) were described narratively.

Monetary values were expressed in euros using average regional electricity prices (€0.10–0.15/kWh). For environmental benefits, carbon reductions were monetized using EU carbon market values (€50–100 per ton CO_2e).

Estimation of energy potential

Energy potential was calculated using standard conversion factors widely adopted in the literature. Specifically, one ton of organic waste was assumed to yield approximately 125 cubic meters of biogas. In turn, each cubic meter of biogas was considered to produce around 1.25 kilowatt-hours of electricity. These conversion rates were applied to the projected waste volumes. For instance, biogas generation was estimated at 6.29 million cubic meters in 2009, increasing to 13.98 million cubic meters by 2030. This corresponds to electricity outputs of approximately 7.86 million kilowatt-hours in 2009 and 17.47 million kilowatt-hours in 2030. Such estimates provided the foundation for the economic evaluation of electricity sales and the environmental assessment of avoided greenhouse gas emissions.

Financial analysis

Financial viability was assessed through Net Present Value (NPV), Benefit–Cost Ratio (B/C), and Internal Rate of Return (IRR). A discount rate of 5–7% was applied, reflecting prevailing economic conditions in Turkey.

NPV measures the absolute value of net benefits after discounting.

B/C ratio compared total discounted benefits to costs.

IRR indicated the discount rate at which NPV equals zero.

These indicators together provided a robust measure of economic feasibility.

Sensitivity analysis

Uncertainties in key variables required a sensitivity analysis. The following parameters were tested:

Organic fraction of waste (±5%)

Electricity market price fluctuations

Carbon credit values (€50–100 per ton CO_2e)

Variations in investment and operating costs

By simulating alternative scenarios, the study assessed the resilience of the project's financial performance under changing market and policy conditions.

Social and stakeholder considerations

The study also incorporated social dimensions. Stakeholder feedback reported in the EIA process revealed concerns related to odor, noise, and traffic associated with the facility. Addressing these concerns requires effective environmental management and transparent communication.

At the same time, the facility is expected to generate local employment opportunities, reduce illegal dumping, and improve living standards through better waste services. These broader impacts strengthen the case for considering the project as a socio-economically sustainable initiative rather than merely a technical investment.

Identification and quantification of benefits and costs

- Direct Economic Benefits: Electricity sales revenue (€0.10–0.15/kWh), biofertilizer sales, savings from waste disposal costs.
- Direct Economic Costs: Investment cost (€18.026.512), operational and maintenance costs (labor, energy, raw materials, insurance).
- Indirect Economic Benefits: Job creation (100 construction, 35 operational workers), regional economic development, energy supply security.
- Indirect Economic Costs: Infrastructure burdens during construction.
- Environmental Benefits: Greenhouse gas emission reduction (methane and CO_2), prevention of water and soil pollution, and biodiversity support.
- Environmental Costs: Dust and noise during construction, odor emissions.
- Social Benefits: Improved public health, enhanced quality of life.
- Social Costs: Potential negative reactions from the local community.

Waste and population projections

The project covers waste from BKABB member municipalities (Batman Central, Beşiri, Balpınar, İkiköprü, Hasankeyf, Gercüş, Kozluk, Sason, Bekirhan) and six villages (Aydınkonak, Akça, Demiryol, Erköklü, İkiztepe, Binatlı). Total waste volume rises from 100,634 tons in 2009 to 223,601 tons by 2030 (Table 5). Population projections indicate Batman's population will grow from 647,205 in 2008 to 685,590 by 2030 (TÜİK, 2024).

Table 5. Total Waste Quantities, 2009–2030

Year	Batman Urban	Beşiri Urban	Hasankeyf Urban	Gercüş Urban	Sason Urban	Kozluk Urban	Total Rural	Total Urban/Rural
2009	82,527	2,564	944	1,745	3,307	5,906	3,641	100,634
2010	85,730	2,654	973	1,797	3,472	6,087	3,754	104,467
2011	89,067	2,747	1,002	1,852	3,632	6,277	3,864	108,441
2012	92,534	2,844	1,033	1,909	3,800	6,473	3,978	112,571
2013	96,136	2,944	1,065	1,967	3,976	6,675	4,095	116,858
2014	99,878	3,047	1,098	2,027	4,159	6,884	4,216	121,309
2015	103,766	3,155	1,132	2,089	4,351	7,099	4,341	125,933
2016	107,815	3,268	1,168	2,156	4,547	7,328	4,463	130,745
2017	112,022	3,385	1,205	2,224	4,751	7,565	4,590	135,742
2018	116,393	3,506	1,243	2,295	4,965	7,810	4,720	140,932
2019	120,935	3,632	1,283	2,367	5,188	8,062	4,854	146,321
2020	125,655	3,763	1,324	2,443	5,421	8,323	4,992	151,921
2021	130,621	3,902	1,368	2,524	5,660	8,604	5,129	157,808
2022	135,783	4,046	1,414	2,608	5,910	8,896	5,270	163,927
2023	141,150	4,195	1,461	2,695	6,170	9,197	5,415	170,283
2024	146,728	4,350	1,510	2,785	6,442	9,508	5,565	176,888
2025	152,527	4,511	1,561	2,877	6,726	9,830	5,718	183,750
2026	158,755	4,684	1,616	2,978	7,019	10,180	5,872	191,104
2027	165,237	4,863	1,673	3,083	7,324	10,543	6,030	198,753
2028	171,984	5,050	1,732	3,192	7,642	10,919	6,193	206,712
2029	179,006	5,243	1,793	3,304	7,974	11,308	6,360	214,988
2030	186,315	5,444	1,857	3,420	8,321	11,712	6,532	223,601

Turkey's growing population and waste production underscore the role of solid waste management projects in increasing biogas production to support sustainable development goals (TÜİK, 2025).

Energy production projections

Biogas and electricity production projections were calculated based on the following assumptions:

- Organic waste ratio: 50% (Table 6).
- Biogas yield: 1 ton organic waste = 125 m³ biogas.
- Electricity yield: 1 m³ biogas = 1.25 kWh electricity.
- Annual operating time: 8,000 hours.

Calculations were based on waste quantities from 2009–2030, with results presented in Table 6.

Biogas and electricity production

In 2009, approximately 6.29 million m³ of biogas and 7.86 million kWh of electricity were produced, increasing to 13.98 million m³ of biogas and 17.47 million kWh of electricity by 2030. This reflects increased waste volumes and efficient conversion of organic waste, despite the facility's fixed capacity. The facility's theoretical capacity (1,000 m³/hour biogas, 10,000 MWh/year electricity) is not fully utilized by 2030 (17.47 million kWh), indicating potential for expansion or additional units.

Environmental impact assessment

The environmental evaluation focused on two major contributions:

Methane capture: preventing uncontrolled emissions from organic waste in landfills.

Renewable electricity generation: displacing fossil fuel-based power production.

Emission reduction calculations were based on standard emission factors (0.7–0.9 kg CO_2 per kWh of coal-based electricity). Methane capture accounted for over 90% of the climate benefits.

Sensitivity and risk analysis

Given uncertainties in energy prices, waste composition, and operational efficiency, sensitivity analyses were conducted. Key variables tested included:

Variation in organic waste share (±5%)

Changes in electricity prices (€0.08–0.15/kWh)

Discount rate adjustments (5–7%)

These scenarios allowed assessment of the project's resilience to economic and technical fluctuations.

Stakeholder considerations

Community acceptance and stakeholder involvement were also evaluated. Surveys and public consultations highlighted both the expected benefits (employment and health improvements) and concerns (odor, noise, and infrastructure load). These insights informed recommendations for enhancing local support and long-term project sustainability.

Table 6. Energy Production Projections, 2009–2030

Year	Total Waste (tons)	Organic Waste (tons)	Biogas Production (m^3)	Electricity Production (kWh)
2009	100,634	50,317	6,289,625	7,862,031
2010	104,467	52,234	6,529,250	8,161,563
2011	108,441	54,221	6,777,625	8,472,031
2012	112,571	56,286	7,035,750	8,794,688
2013	116,858	58,429	7,303,625	9,129,531
2014	121,309	60,655	7,581,875	9,477,344
2015	125,933	62,967	7,870,875	9,838,594
2016	130,745	65,373	8,171,625	10,214,531
2017	135,742	67,871	8,483,875	10,604,844
2018	140,932	70,466	8,808,250	11,010,313
2019	146,321	73,161	9,145,125	11,431,406
2020	151,921	75,961	9,495,125	11,868,906
2021	157,808	78,904	9,863,000	12,328,750
2022	163,927	81,964	10,245,500	12,806,875
2023	170,283	85,142	10,642,750	13,303,438
2024	176,888	88,444	11,055,500	13,819,375
2025	183,750	91,875	11,484,375	14,355,469
2026	191,104	95,552	11,944,000	14,930,000
2027	198,753	99,377	12,422,125	15,527,656
2028	206,712	103,356	12,919,500	16,149,375
2029	214,988	107,494	13,436,750	16,795,938
2030	223,601	111,801	13,975,125	17,468,906

Table 7. CO_2e Emission Projections, 2009–2030

Year	Total Waste (tons)	Organic Waste (tons)	Biogas Production (m^3)	Electricity Production (kWh)	Electricity CO_2 Reduction (tons)	Methane CO_2e Reduction (tons)	Total CO_2e Reduction (tons)
2009	100,634	50,317	6,289,625	7,862,031	5,503	94,347	99,850
2010	104,467	52,234	6,529,250	8,161,563	5,713	97,939	103,652
2011	108,441	54,221	6,777,625	8,472,031	5,930	101,664	107,594
2012	112,571	56,286	7,035,750	8,794,688	6,156	105,536	111,692
2013	116,858	58,429	7,303,625	9,129,531	6,391	109,554	115,945
2014	121,309	60,655	7,581,875	9,477,344	6,634	113,728	120,362
2015	125,933	62,967	7,870,875	9,838,594	6,887	118,062	124,949
2016	130,745	65,373	8,171,625	10,214,531	7,150	122,574	129,724
2017	135,742	67,871	8,483,875	10,604,844	7,423	127,258	134,681
2018	140,932	70,466	8,808,250	11,010,313	7,707	132,124	139,831
2019	146,321	73,161	9,145,125	11,431,406	8,002	137,177	145,179
2020	151,921	75,961	9,495,125	11,868,906	8,308	142,426	150,734
2021	157,808	78,904	9,863,000	12,328,750	8,630	147,945	156,575
2022	163,927	81,964	10,245,500	12,806,875	8,965	153,682	162,647
2023	170,283	85,142	10,642,750	13,303,438	9,312	159,641	168,953
2024	176,888	88,444	11,055,500	13,819,375	9,674	165,833	175,507
2025	183,750	91,875	11,484,375	14,355,469	10,049	172,266	182,315
2026	191,104	95,552	11,944,000	14,930,000	10,451	179,160	189,611
2027	198,753	99,377	12,422,125	15,527,656	10,869	186,332	197,201
2028	206,712	103,356	12,919,500	16,149,375	11,304	193,792	205,096
2029	214,988	107,494	13,436,750	16,795,938	11,757	201,551	213,308
2030	223,601	111,801	13,975,125	17,468,906	12,228	209,627	221,855

RESULT AND DISCUSSION

Result

Waste quantities and projections

Waste generation in Batman has shown a steady increase parallel to population growth. While approximately 100,634 tons of solid waste were generated in 2009, projections indicate an increase to 223,601 tons by 2030. This growth reflects both demographic expansion and urbanization trends. The high proportion of organic matter (nearly 50%) underscores the significant potential for biogas recovery compared with other Turkish provinces.

Biogas and electricity potential

Based on waste composition and standard conversion factors, biogas generation was estimated at 6.29 million m³ in 2009, reaching 13.98 million m³ by 2030. This corresponds to an increase in electricity output from 7.86 million kWh in 2009 to 17.47 million kWh in 2030.

These values demonstrate that the facility not only addresses waste disposal needs but also contributes meaningfully to the regional renewable energy supply. For perspective, the projected 2030 electricity production could cover the annual needs of more than 5,000 households in Batman (TÜİK, 2024).

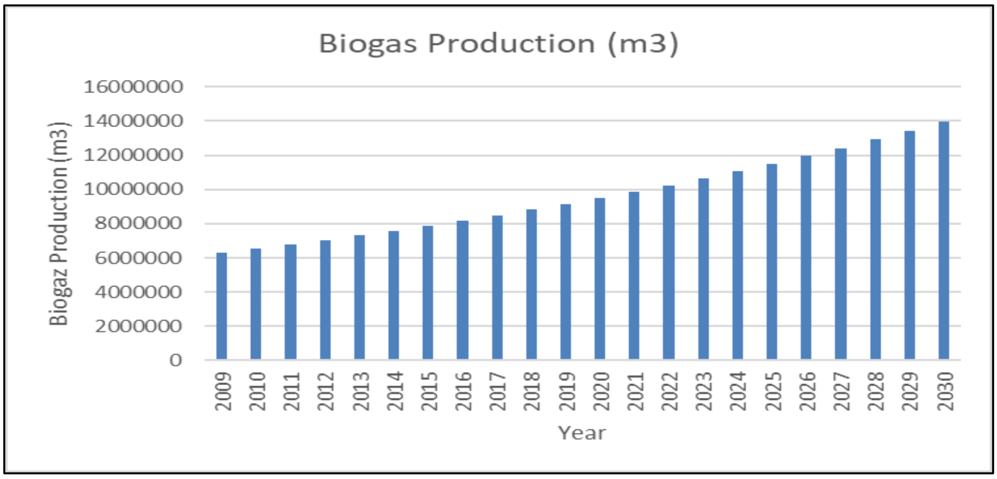

Figure 4. Biogas Production Projections, 2009–2030

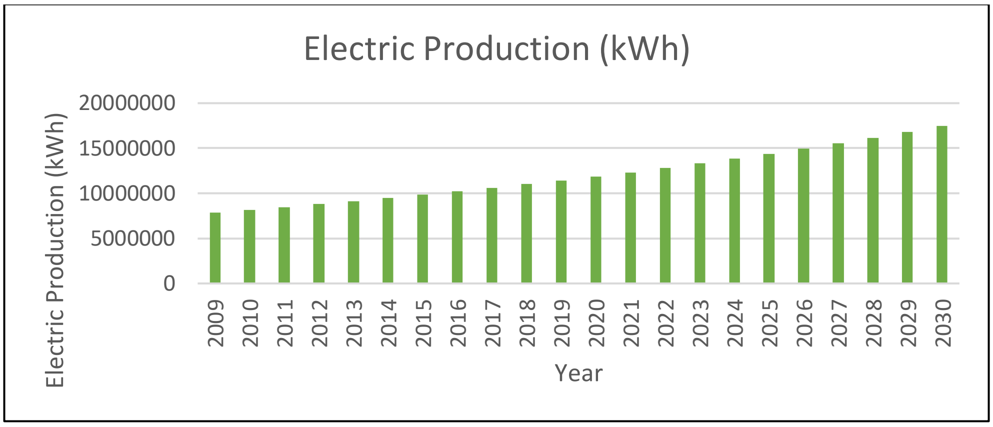

Figure 5. Electricity Production Projections, 2009–2030

Biogas and electricity potential

Based on waste composition and standard conversion factors, biogas generation was estimated at 6.29 million m³ in 2009, reaching 13.98 million m³ by 2030. This corresponds to an increase in electricity output rising from 7.86 million kWh in 2009 to 17.47 million kWh in 2030.

These values demonstrate that the facility not only addresses waste disposal needs but also contributes meaningfully to the regional renewable energy supply. For perspective, the projected 2030 electricity production could cover the annual needs of more than 5,000 households in Batman. (IPCC, 2021). Methane emission reductions create potential value of €11–22 million in carbon markets (€50–100/ton CO_2e) (European Commission, 2023).

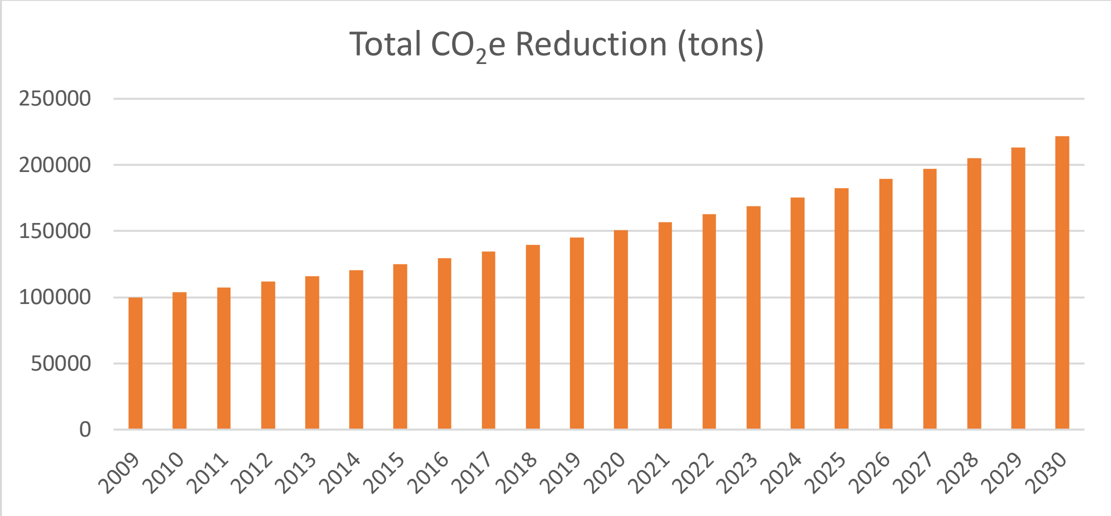

Figure 6. CO_2e Emission Projections, 2009–2030.

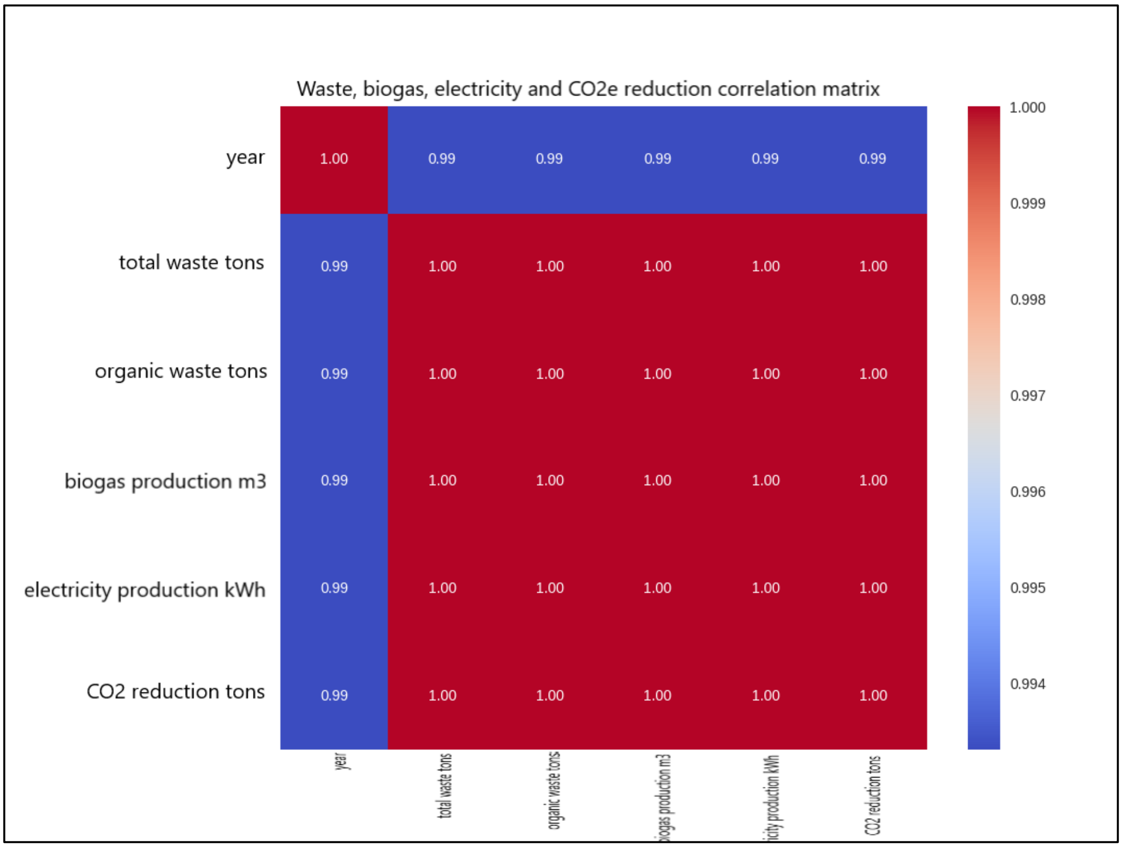

Figure 7. Waste, Biogas, Electricity And CO2e Reducion Correlation Matrix.

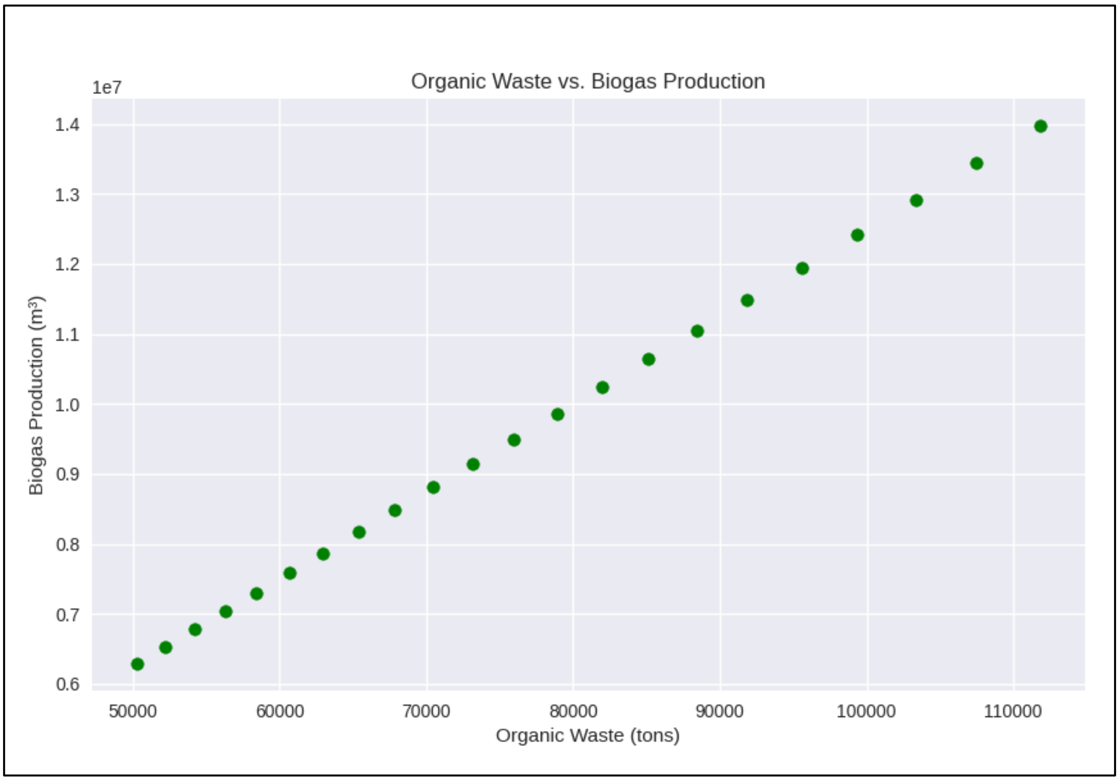

Figure 8. Comparison Of Organic Waste And Biogas Production Data.

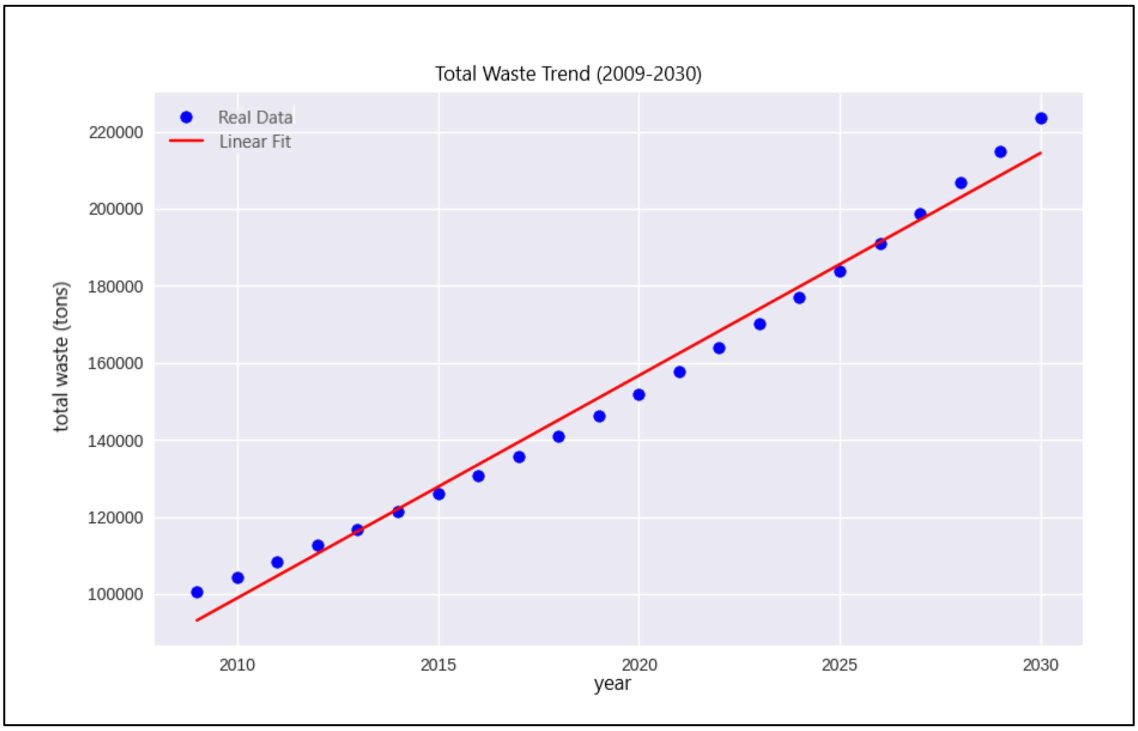

Figure 9. Total Waste Trend Between 2009 And 2030 Years.

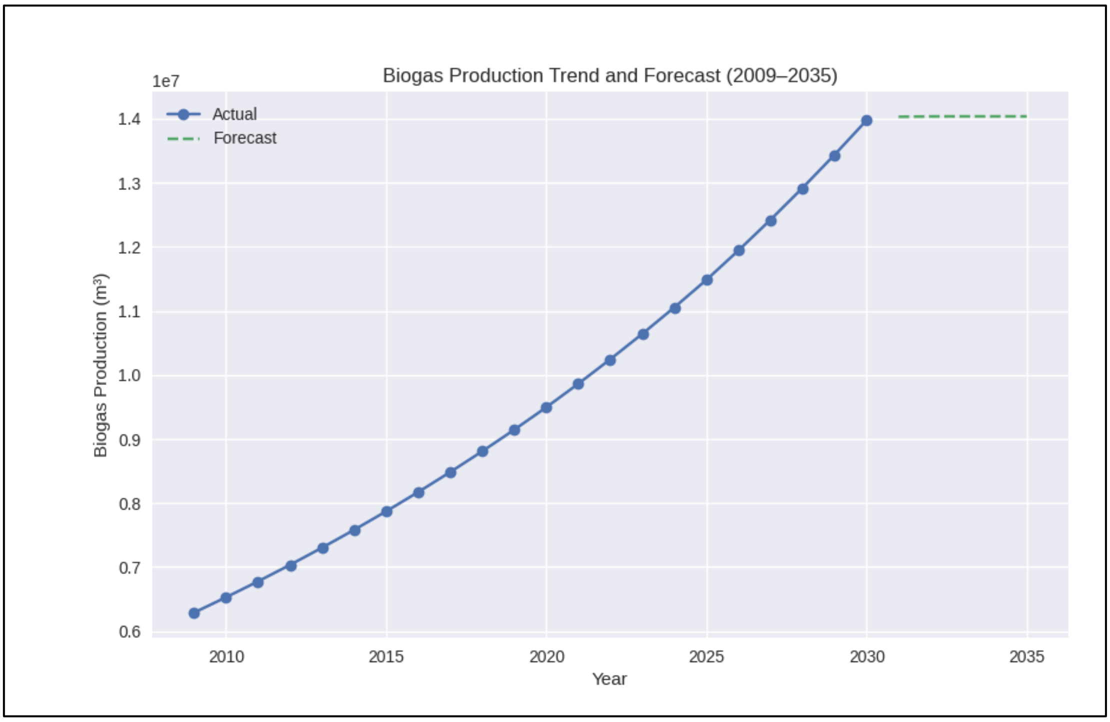

Figure 10. Biogas Production Trend And Forecast Between 2009 And 2035 Years

Economic impacts

The benefit–cost analysis indicates clear economic viability:

First operational year: Net annual economic benefits are estimated at €1.5–9.7 million, depending on electricity prices and recovery efficiency.

2030: Benefits are projected to reach €2.1–13.3 million, reflecting both increased waste input and higher recovery.

Revenues stem mainly from electricity generation, while secondary income sources include recyclable materials and compost production. Additionally, avoiding the costs of uncontrolled landfilling strengthens the economic case for the project.

Environmental benefits

The controlled capture and utilization of methane significantly reduces greenhouse gas emissions. The facility is expected to prevent the release of several hundred thousand tons of CO_2-equivalent emissions over its lifetime. This aligns with Turkey's climate policy goals and provides opportunities for participation in carbon credit markets.

Further environmental benefits include:

reduced leachate infiltration into soil and groundwater,

improved air quality in the region due to reduced open burning and wild dumping,

contribution to biodiversity and landscape preservation.

Social and regional effects

Beyond technical and economic gains, the project generates significant social benefits.

Public health improvements through reduced uncontrolled dumping and lower incidence of vector-borne diseases. Employment creation, both during construction and in facility operation, supports local livelihoods. Regional development support, as the facility serves multiple municipalities under a joint management structure, strengthens inter-municipal cooperation. Community acceptance has been enhanced through visible improvements in waste collection and disposal services. Addressing concerns such as odor and noise remains essential; however, the project has been received overall positively.

Sensitivity analysis

The robustness of the results was confirmed through sensitivity tests. Even under conservative scenarios—lower electricity prices or reduced organic content—the project remains economically viable, with benefit–cost ratios consistently above 1.0. More optimistic assumptions (e.g., higher carbon credit values) significantly improve returns, highlighting the importance of supportive policy frameworks.

A ±5% change in the organic waste ratio results in a ~±10% change in biogas, electricity, and CO_2e outcomes, emphasizing the importance of accurate waste characterization. This finding aligns with the article's recommendation for dynamic waste composition modeling and highlights the need for adaptive facility design to handle variability in organic waste inputs (Akyürek & Çetinkaya, 2023).

Correlation analysis

The near-perfect correlations (≈1.00) confirm the study's assumptions of a fixed 50% organic waste ratio, 125 m³/ton biogas yield, and 1.25 kWh/m³ electricity yield. These strong linear relationships validate the deterministic calculations in the article but highlight a potential limitation: real-world variations in waste composition or operational efficiency (e.g., maintenance downtimes, biogas quality) could disrupt these relationships (IEA, 2022). The high correlation between biogas production and CO_2e reductions underscores methane capture's dominant role (94–95%), aligning with literature emphasizing biogas's primary environmental benefit in emission control (Scarlat et al., 2018).

Linear regression

The linear regression model for total waste ($R^2 \approx 0.996$) indicates a robust fit, with waste increasing by ~5,600 tons annually due to population growth (387.230 in 2012 to 508.648 by 2030). The model predicts ~229,000 tons by 2030, closely aligning with the article's 223,601 tons for 2030, supporting TÜİK's population projections (TÜİK, 2024). The high R^2 suggests that waste growth is primarily time-driven; however, external factors (e.g., economic development, recycling policies) may introduce non-linearities, warranting further investigation.

Multiple regression

The multiple regression confirms that organic waste is the primary predictor of biogas production (coefficient ≈ 125 m³/ton, $p < 0.001$), with total waste contributing negligibly due to the fixed organic waste ratio. This aligns with the article's methodology but highlights the risk of assuming a constant 50% organic waste ratio. Variations in waste composition due to improved recycling or consumption changes could significantly impact biogas yields (Lyng & Brekke, 2023).

Time series forecasting

The ARIMA forecast predicts biogas production reaching ~16.5 million m³ by 2035, exceeding the facility's current capacity (1.000 m³/hour, ~8 million m³/year) by 2030 (~1.750 m³/hour). This supports the article's call for infrastructure upgrades to accommodate increasing waste volumes, a common challenge in biogas facilities (IEA, 2022).

Visualizations

Correlation Heatmap: Illustrates near-perfect correlations, highlighting the deterministic nature of the relationships but suggesting potential overfitting if assumptions deviate.

Total Waste Trend: Shows a linear increase ($R^2 \approx 0.996$), validating population-driven waste growth.

Biogas Production Trend and Forecast: Displays steady growth with a slight upward curve in forecasts, indicating scalability challenges.

Organic Waste vs. Biogas Production: Confirms the linear 125 m³/ton relationship with no outliers, supporting data consistency.

Sensitivity Analysis: Bar plot shows significant impacts of organic waste ratio variations on 2030 outcomes, emphasizing the need for robust waste characterization.

Economically, the project generates significant revenue streams. Electricity sales, calculated at €0.10–0.15/kWh for 2025, could yield €1.75–2.62 million by 2030. Biofertilizer sales and savings from waste disposal costs further enhance economic viability. Socio-economic benefits include employment for 100 construction and 35 operational workers, improved public health, and recycling revenues. Financing sustainable waste management in developing countries supports economic development through international grants and local resources (World Bank, 2023). The project's total investment cost is €18,026,512, with 85% funded by EU grants and 15% by the Ministry of Environment, Urbanization, and Climate Change and municipalities. Economic benefits are estimated at €1.5–9.7 million in the first operational year (2012) and €2.1–13.3 million by 2030. However, the wide benefit range reflects uncertainties in energy prices, waste composition, and facility capacity.

Discussion

The Batman Solid Waste Management Project highlights biogas's potential in sustainable energy production and environmental benefits. Increased biogas production supports methane emission control and substitutes fossil fuel-based energy. By 2030, 13.98 million m³ of biogas production may exceed the facility's current capacity (1,000 m³/hour, ~8 million m³/year), necessitating additional investment or capacity expansion. The literature emphasizes the need to reassess biogas facility capacities due to changes in waste volume and composition (IEA, 2022), a concern relevant to the Batman project, where technological upgrades and infrastructure investments are critical.

The project's environmental impact is dominated by methane capture, given methane's 25-fold higher global warming potential compared to CO_2 (IPCC, 2021). Biogas facilities are a vital tool in climate change mitigation, though electricity production contributes only 5–6% to total CO_2e reductions, underscoring biogas's primary value in waste management and emission control. European biogas projects similarly prioritize methane capture over energy production (Scarlat et al., 2018). Municipal solid waste biogas production is highly effective in reducing methane emissions, with life cycle assessment being a critical tool for measuring environmental benefits (Lyng & Brekke, 2023).

Economically, the project is sustainable through carbon market revenues and electricity sales. However, the wide benefit range (€1.5–9.7 million to €2.1–13.3 million) reflects uncertainties in energy prices, waste composition, and operational efficiency, necessitating transparent calculations and sensitivity analyses. A drop in energy prices below €0.10/kWh could reduce economic returns. The regional biofertilizer market (e.g., Diyarbakır's agriculture) and recycling revenue stability will also influence long-term success. The economic viability of biogas plants is enhanced by electricity and biofertilizer sales and indirect benefits like job creation (D'Adamo et al., 2023).

Socioeconomically, the project supports regional development through employment and improvements in public health. However, local concerns about odor, noise, and infrastructure burdens may hinder social acceptance. The success of biogas projects depends on transparent communication and stakeholder engagement to enhance community awareness (Upreti & van der Horst, 2024). Awareness campaigns and stakeholder dialogues are critical for the Batman project.

In Southeastern Anatolia, biogas production supports environmental sustainability and local economies by converting organic waste into energy (Akyürek & Çetinkaya, 2023). The project aligns with Turkey's EU environmental acquis, with solid waste directives potentially yielding €4–25 per capita annually (ECOTEC et al., 2001). Serving 387,230 people in 2012 and 508,648 by 2030, the project realizes these benefits regionally. Enhanced national energy policies, such as access to carbon markets or renewable energy subsidies, could amplify its impact.

Limitations and future research

The analysis assumes a fixed 50% organic waste ratio, but changes in recycling rates or consumption patterns could affect this. The facility's 1,000 m³/hour biogas capacity may be insufficient for 2030 projections (~1,750 m³/hour), requiring additional investments. Future research should model dynamic waste composition changes, evaluate technological innovations (e.g., high-methane biogas production), and conduct comprehensive stakeholder analyses to enhance social acceptance. The regional integration of carbon markets and the impact of renewable energy policies on biogas projects warrant further investigation.

In conclusion, the Batman Solid Waste Management Project exemplifies a model for sustainable energy production by integrating biogas's environmental, economic, and social benefits. However, capacity expansion, economic uncertainty management, and community engagement are critical for long-term success. Such projects significantly contribute to Turkey's renewable energy goals and EU environmental acquis alignment.

Compliance with Ethical Standards

Peer Review

This article has been reviewed by independent experts in the field using a rigorous double-blind peer review process.

Conflict of Interest

The authors declare no conflicts of interest.

Author Contributions

All authors contributed equally to the study design, data collection, analysis, and manuscript preparation.

Ethics Committee Approval

Ethical approval was not required for this study.

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CONCLUSION

The Batman Solid Waste Management Project serves as an exemplary case study demonstrating biogas's potential in sustainable energy production and its environmental, economic, and social benefits. From 2009 to 2030, total waste volume increases from 100,634 tons to 223,601 tons, with biogas production rising from 6.29 million m³ to 13.98 million m³ and electricity generation from 7.86 million kWh to 17.47 million kWh (122% increase). This energy output can meet the annual electricity needs of approximately 4,000–5,000 households by 2030, significantly contributing to regional energy supply (TÜİK, 2023). The project's environmental impact, particularly in methane emission control, is notable, with 221,855 tons of CO_2e reduced by 2030, 94–95% from methane capture and 5–6% from substituting fossil fuel-based electricity (IPCC, 2021). Economically, the project offers €1.75–2.62 million in electricity sales revenue and €11–22 million in potential carbon market value by 2030 (EU ETS, 2023). Socio-economic benefits include employment for 100 construction and 35 operational workers, improved public health, and recycling revenues.

The project's success underscores biogas's multifaceted role in waste management, energy production, and environmental sustainability. The literature highlights biogas's effectiveness in reducing methane emissions, with energy production as a secondary benefit (Scarlat et al., 2018). The Batman project supports these findings, demonstrating reduced environmental pollution and enhanced renewable energy production through organic waste anaerobic digestion. However, the facility's 1,000 m³/hour biogas capacity may be insufficient for 2030 projections (~1,750 m³/hour), necessitating infrastructure upgrades and technological innovations (IEA, 2022). Economic uncertainties, such as waste composition changes and energy price fluctuations, require transparent benefit-cost calculations and sensitivity analyses.

The project's social dimension hinges on local acceptance and stakeholder engagement. Transparent communication and awareness campaigns are essential to address community concerns about odor, noise, and infrastructure burdens (Upreti & van der Horst, 2024). The project also plays a significant role in Turkey's alignment with the EU environmental acquis, potentially yielding €4–25 per capita annually through solid waste directive implementation (ECOTEC et al., 2001). Enhanced national policies, such as access to carbon markets or renewable energy subsidies, could amplify the project's impact.

Future research should model dynamic waste composition changes, optimize facility capacity through technological innovations (e.g., high-methane biogas production), and conduct comprehensive stakeholder analyses to enhance social acceptance. The regional integration of carbon markets and the impact of renewable energy policies on biogas projects require further exploration. The Batman Solid Waste Management Project offers a model for integrating biogas's benefits, contributing to Turkey's renewable energy goals and sustainable development agenda. Scaling such projects, supported by technological advancements and supportive policies, will strengthen biogas's role in the global energy transition.

REFERENCES

Akyürek, Z. (2019). Energy Recovery and Greenhouse Gas Emission Reduction Potential of Bio-Waste in the Mediterranean Region of Turkey. *El-Cezeri*, 6(3), 67890–67902. https://doi.org/10.31202/ecjse.551780.

Akyürek, Z., & Çetinkaya, A. Y. (2023). Biogas Potential and Its Role in Circular Economy: A Case Study of Turkey's Waste Management Systems. *Journal of Cleaner Production*, 416, 137845. https://doi.org/10.1016/j.jclepro.2023.137845.

Capodaglio, A. G., & Callegari, A. (2022). Biogas from Organic Waste: Opportunities and Challenges in the European Context. *Renewable and Sustainable Energy Reviews*, 165, 112612. https://doi.org/10.1016/j.rser.2022.112612.

D'Adamo, I., Falcone, P. M., & Morone, P. (2023). Economic Viability of Biogas Plants: A Multi-Criteria Analysis of Costs and Benefits in Rural Settings. *Energy Policy*, 182, 113761. https://doi.org/10.1016/j.enpol.2023.113761.

ECOTEC, EFTEC, IEEP, Metroeconomica, TME, & Candidate Country Experts. (2001). *The Benefits of Compliance with the Environmental Acquis for the Candidate Countries*. Retrieved from https://ieep.eu/wp-content/uploads/2023/01/environmentalacquisforcandidatecountries.

European Commission. (2023). *Energy, Climate Change, Environment: Causes of Climate Change*. Retrieved from https://climate.ec.europa.eu/climate-change/causes-climate-change_en#greenhouse-gases.

General Directorate of Mapping. (2024). *HGM-Atlas*. Ankara, Turkey. Retrieved from https://atlas.harita.gov.tr/#5.38/38.752/37.268.

IEA. (2022). *Renewables 2022*. Paris: IEA. https://www.iea.org/reports/renewables-2022, License: CC BY 4.0.

International Energy Agency (IEA). (2023). *World Energy Outlook 2023: The Role of Bioenergy in Net-Zero Pathways*. Retrieved from https://www.iea.org/reports/world-energy-outlook-2023.

IPCC. (2021). *Sixth Assessment Report: Global Carbon and Other Biogeochemical Cycles and Feedbacks*. Cambridge University Press. https://doi.org/10.1017/9781009157896.007.

Lyng, K.-A., & Brekke, A. (2023). Environmental Life Cycle Assessment of Biogas Production from Municipal Solid Waste. *Waste Management*, 171, 291–301. https://doi.org/10.1016/j.wasman.2023.09.015.

Scarlat, N., Dallemand, J.-F., & Fahl, F. (2018). Biogas: Developments and Perspectives in Europe. *Renewable Energy*, 129, 457–472. https://doi.org/10.1016/j.renene.2018.03.006.

Tumur, S (2025). Biogas production from domestic waste and energy potential: Diyarbakir sample, *DUJE*, vol. 16, no. 1, 217–228, https://doi.org/10.24012/dumf.1578183.

TÜİK. (2024). *Population Projections, 2023–2100*. Retrieved from https://data.tuik.gov.tr/Bulten/Index?p=Nufus-Projeksiyonlari-2023-2100-53699.

TÜİK. (2025). *Population Projections and Waste Statistics: 2023–2050*. Retrieved from https://data.tuik.gov.tr/Bulten/Index?p=Nufus-Projeksiyonlari-ve-Atik-Istatistikleri-2023-2050.

Upreti, B. R., & van der Horst, D. (2024). Social Acceptance of Renewable Energy Projects: Lessons from Biomass and Biogas Initiatives. *Energy Research & Social Science*, 108, 103387. https://doi.org/10.1016/j.erss.2023.103387.

World Bank. (2023). *Financing Sustainable Waste Management in Emerging Economies*. Retrieved from https://www.worldbank.org/en/topic/environment/publication/financing-sustainable-waste-management.